Taking Control of the Virtual World – Novel Perspectives on Interaction in Virtual Environments

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Publications and Submissions

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Abstract

Once a topic only for researchers and enthusiasts, virtual reality (VR) has recently developed into a widely available platform with huge potential. However, we are still far from tapping the full potential of virtual environments. Whereas one might argue that the reasons reside in the low prevalence of headsets or the necessity for further technical advancements, we see a primary reason in the expectations for VR. Often, it is tempting to copy tried-and-tested interactions and interfaces from non-VR applications or replace established approaches and workflows that work well without a VR headset. Instead, we want to think outside the box and design techniques "VR-first" that leverage the unique advantages VR offers.

In this dissertation, we explore how to design the interaction with virtual worlds to achieve a natural and fluent VR experience. Our work spans four essential aspects of VR research: locomotion, interaction, perspectives, and applications. First, we contribute to the field of locomotion research by establishing four unique navigation concepts that either target decisive gaps in the literature or improve existing approaches. Next, we focus on the interaction within the VR environment by presenting our efforts in understanding user behavior, imagining novel input modalities, and structuring interface design. Afterward, we extend the sensation of owning a virtual body in VR to animal avatars and investigate the potential of multiprotagonist narratives where users switch between different characters. In the last part, we cover the general use of VR in everyday life. Therefore, we explore how non-VR audiences can watch the user's experience in the virtual world. We also demonstrate the potential of full-body exercises in VR by designing an exergame for safe and engaging jump training. Finally, we conclude the dissertation with a general discussion of the presented concepts and a critical look at our research and its potential impact.

Abstract – German

Ursprünglich ein Thema für Forscher und Enthusiasten, hat sich die virtuelle Realität (VR) zu einer vielversprechenden Plattform mit vielen Einsatzmöglichkeiten entwickelt. Wir sind jedoch noch weit davon entfernt, das volle Potenzial virtueller Umgebungen auszuschöpfen. Während die Gründe auch in der geringen Verbreitung oder verbleibenden technischen Hürden liegen, sehen wir einen Hauptgrund in den Erwartungen an VR. Auch wenn es zunächst verlockend erscheint, bewährte Interaktionskonzepte oder Prozesse für VR zu adaptieren, sind wir davon überzeugt, dass man von Grund auf neue, exklusiv auf VR-Headsets zugeschnittene, Techniken entwicklen muss, um die vollständige Bandbreite einzigartiger Vorteile zu nutzen.

In dieser Dissertation erforschen wir, wie man Interaktionen so designen kann, dass sie sich natürlich und intuitiv anfühlen. Dazu umfasst die vorliegende wissenschaftliche Arbeit vier Hauptpfeiler der VR-Forschung: Fortbewegung, Interaktion, Perspektiven und Anwendungsfälle. Zuerst erweitern wir die Sammlung bestehender Fortbewegungsarten um vier neue Konzepte, die bestehende Lücken in der Literatur schließen oder bereits etablierte Ansätze verbessern. Im zweiten Teil beschäftigen wir uns mit der Interaktion in virtuellen Umgebungen. Zu diesem Zweck untersuchen wir, wie sich Nutzer in VR verhalten, bevor wir uns der Entwicklung von neuen Interaktionskonzepten und dem Design von Inventaren widmen. Im Anschluss erweitern wir das Konzept der virtuellen Verkörperung auf Tier-Avatar und untersuchen, wie man in VR zwischen verschiedenen Charakteren wechseln kann, um komplexe Geschichten aus verschiedenen Blickwinkeln zu erzählen. Abschließend beleuchten wir zwei anwendungsbezogene Aspekte. Zuerst untersuchen wir, wie Nicht-VR-Zuschauer dem VR-Nutzer zugucken können. Außerdem entwickeln wir ein VR-Exergame, mit dem Nutzer spielerisch ihre Sprungkraft üben und technisches Feedback erhalten. In der abschließenden Diskussion bewerten wir die vorgestellten Konzepte und ihren zukünftigen Beitrag für die VR-Forschung kritisch.

Contents

1 Introduction

In the last decade, virtual reality (VR) has evolved from a topic for researchers and enthusiasts to a widely available platform. VR headsets have dropped considerably in price and now do not cost more than a console while being lightweight and mobile. Consumer devices such as the Meta Quest 2 or the Vive Focus can provide the necessary foundation for a broader application in various use cases. Additionally, digitization skyrocketed with the outbreak of the COVID-19 pandemic in 2020. Despite the urgent need for virtual solutions, VR has not yet replaced video conferences, traditional classroom learning, or on-site training. One could argue that too few people own VR headsets or that more technical advancement is needed first to make VR systems more powerful and comfortable. Whereas both are valid concerns, the primary reason might already start with the expectations for VR.

Instead of searching for use cases in which VR ought to replace established approaches and workflows, we argue that its greatest potential resides in realizing novel experiences that are not possible using traditional monitors. For example, immersive experiences are helpful for presenting highly complex multidimensional data comprehensibly or letting users experience a scenario that is otherwise too difficult or dangerous to undergo in real life. However, in many cases, traditional screens or augmented reality (AR) are more suitable for displaying additional information or transporting knowledge in a comprehensible way.

Furthermore, practical VR applications are not achieved by simply rendering existing content on a stereoscopic head-mounted display (HMD). Instead, VR environments replace the entire desktop experience we have used for years. Even though VR developers usually aim to mimic the real world and our interaction within very closely, VR experiences do not need to replicate every aspect. For instance, it makes no practical sense to force users to walk miles and miles between two points just because that is how reality is designed. Additionally, we cannot replicate every aspect of reality yet. Prototypes targeting advanced senses, such as olfaction or gustation, have not yet reached the technical soundness to be incorporated in commercially available headsets.

However, this limited realism is also one of the core strengths of VR and allows it to realize experiences that are not completely illusory but also not entirely realistic. For instance, users can exchange their physical body with a virtual avatar that differs greatly from their normal appearance and could even be nonhumanoid, like an animal. Other applications allow users to experience a deeply personal and immersive story from multiple perspectives and thereby understand the motives of different protagonists. Lastly, VR exergames can turn repetitive physical exercises into engaging and eclectic experiences people can use at home to exercise. These are just some of the projects covered in this dissertation. Our other research also takes a closer look at the fundamental interaction concepts needed for VR experiences in general. However, whether the contribution is a novel locomotion approach, input modality, or spectator experience, our inherent research motivation remains identical: We want to think outside the box and create techniques designed from the ground up to realize the full potential of current VR systems.

Whereas classical desktop experiences limit the users to abstracted two-dimensional inputs with a keyboard and mouse while viewing the scenario on a monitor, VR emphasizes the spatiality of the world and the user's actions within. Potentially, the most potent advancement over prior computer interfaces is the ability to interact with the application in a highly familiar and natural manner by moving physically through the three-dimensional (3D) world and interacting with virtual objects using spatially tracked hands or even the whole body. At the same time, this aspect is also one of the most intriguing topics in VR research. The often-noted stereoscopic rendering is not an exclusive invention for immersive HMDs but has a long history in 3D displays and films. However, interacting with user interfaces and objects within the virtual world directly challenges the established principles of user experience design.

Developers should never directly copy their tried-and-tested interactions and interfaces from non-VR applications. Instead, user experience profits from designing techniques "VR-first" and leveraging the unique advantages VR offers. This dissertation explores how to design the interaction with virtual worlds to achieve a natural and fluent VR experience. Our work spans various essential building blocks of most VR applications, including locomotion concepts, input modalities, user interfaces, and transition techniques. Apart from developing original prototypes that build upon the reality-extending nature of VR, we also evaluate and compare existing concepts and investigate how users interact with the virtual experience. Thereby, we advance the understanding of user behavior in virtual environments, spark novel research directions, and provide practitioners with the right tools to design pleasant and meaningful experiences.

1.1 Scope of this Thesis

Interaction in and with VR applications is an extensive domain in human-computer interaction (HCI) and user experience (UX) research. Our work builds on a long list of prior publications, all contributing puzzle pieces to the ultimate question:

How can we design a virtual experience that feels natural and fluent?

With our work, we want to contribute novel perspectives to this growing field of research. Therefore, we present original interaction concepts that are not necessarily realistic in a physical sense but feel natural in VR. For example, we propose a locomotion technique based on dynamic perspective switches. Furthermore, we aim to understand how users interact in VR by conducting user studies on topics like collision behavior or nonhuman embodiment. Lastly, we explore promising new research directions, such as multiprotagonist narratives or exergames that train the whole body.

We subdivide the overarching research question into four separate chapters, each addressing one fundamental aspect of virtual experiences (see Figure 1.1):

Locomotion — *How do we move through extensive virtual environments?*
VR environments may range from the size of small rooms to entire virtual worlds spanning many square kilometers. Therefore, a proper locomotion technique is vital not only for exploration but also to travel between different interaction points. However, as both the virtual environment and real tracking space may vary greatly in shape and size, no concept suits every combination. We introduce, evaluate, and discuss four unique locomotion techniques targeting different settings.

Interaction — *How can we interact with our virtual surroundings?*
VR applications require that the users behave as expected and can interact with the world as intended. Therefore, we cover three interaction-related topics in this chapter. First, we investigate if users still conform to the virtual world's rules when they know that obstacles are only virtual and may safely be ignored. Next, we explore the design of novel input modalities that use the user's gait instead of the usual hand-based interaction. Lastly, we develop a taxonomy providing an overview of the available design elements of item storage interfaces in VR applications.

Perspectives — *Whom do we become when entering a virtual world?*
In contrast to other forms of media, VR has the unique potential to realize otherwise impossible scenarios and increase immersion over the usual degree. One central aspect of this experience is the sensation of embodying different persons with other body shapes and character traits. We take this sensation further by extending it to animal

embodiment and investigating the potential of multiprotagonist narratives in VR where users dynamically switch between different characters.

Applications — *How can we use VR in everyday life?*
In the final part, we cover the general use of VR experiences in everyday life. First, we take a closer look at the spectator experience. One major challenge of VR is that only one person can wear the headset simultaneously, blocking contact with other observers. First, we investigate how the viewing perspective influences the audience's experience. In a second step, we develop a mirror device with which bystanders can observe the user's actions in VR from their preferred viewpoint. In the second part of this chapter, we demonstrate how VR experiences can help train the complete body. Therefore, we use the input from domain experts to design an exergame for safe and engaging jump training in VR.

1.2 Focus on VR Games

Most of our research projects primarily target VR games. This form of entertainment media is one of the most common uses of VR devices among consumers and has mainly fueled headset sales in recent years. Of course, many other areas employ virtual experiences very successfully as well, and one might argue perfunctorily that our limitation to one discipline limits the impact of our contribution to the research community. In contrast, we argue that games are exceptionally well suited for testing novel interaction concepts for the first time compared to many other domains.

Even though many people enjoy games occasionally, most of them would not classify themselves as highly proficient gamers, and even fewer have played VR games before. Nevertheless, such experiences should be playable and enjoyable for everyone regardless of their proficiency level. This characteristic make games a tough testing ground for any research idea. Additionally, games and other forms of media often depend on a strong feeling of immersion. Players are usually more sensitive to interruptions in presence induced by an inadequate interaction technique compared to other domains, such as scientific visualization. Lastly, conducting studies using a gamified scenario dramatically increases the potential pool of participants. In contrast to highly domain-specific contexts, almost everyone can participate and give valuable feedback.

These three reasons mainly fueled our decisions to target VR games first. Despite this focus, the vast majority of our contributions are easily transferable to other use cases of immersive VR. For example, our locomotion techniques are not solely designed for

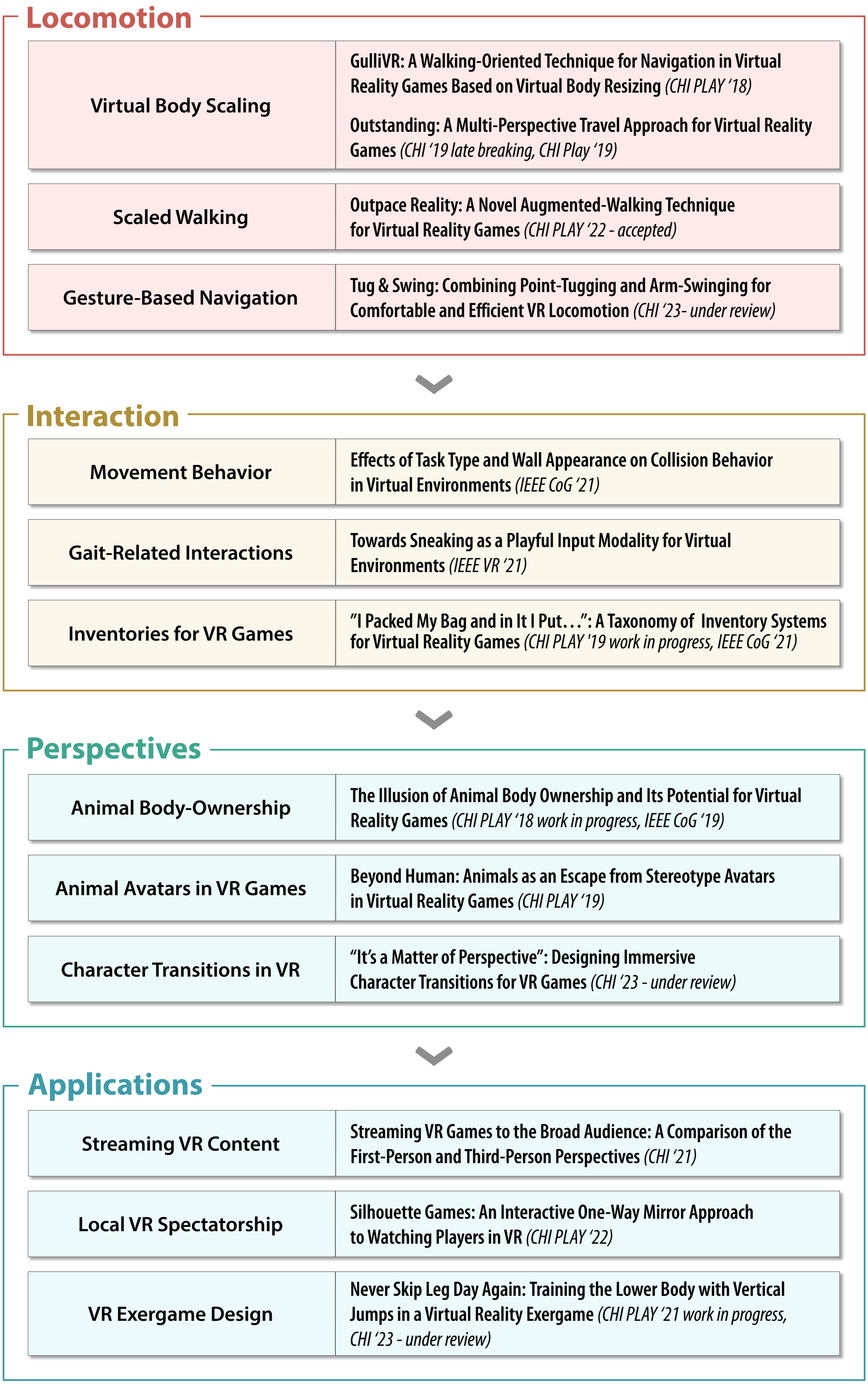

Figure 1.1: Overview of the dissertation's structure. To preserve legibility, we only list the titles of the respective full-paper publications.

entertaining scenarios but work in every virtual environment that fulfills their requirements.

1.3 Dissertation Structure

This cumulative dissertation consists of two parts: a synopsis and a collection of publications that form the body of the dissertation. Compared to a monograph, this synopsis does not possess the same depth as a traditional manuscript. Instead, it serves as a guide through the previously published papers by introducing, discussing, and tying the different contributions together. Apart from providing a general overview, it should also invite readers to pause and read the individual publications or parts of them along the way. Therefore, the synopsis contains pointers to the related papers, where the readers may find detailed information about the techniques, the conducted study, the exact results and analysis measures, and further discussions.

After the introduction, we start by providing a brief overview of the relevant related work necessary to understand the contributions made. Therefore, we quickly introduce the concepts of immersion, presence, and cybersickness before covering the latest advancements in locomotion and embodiment research. The central part is structured into the four chapters, *Locomotion*, *Interaction*, *Perspectives*, and *Applications*, each covering an essential aspect of VR research. In each chapter, we explain our motivation for the conducted research, the main contributions in the individual papers, and a critical discussion. Finally, we conclude the synopsis with a general discussion of the presented contents and a critical look at the conducted research and its potential impact.

2 Related Work

Before diving into the research work covered in this dissertation, we start by introducing the basic VR concepts required for most projects. In most of our publications, we explore how our concepts influence the user's feeling of being present in the virtual environment. Hence, we begin this chapter by distinguishing the closely related aspects of presence and immersion. Since our concepts typically involve movements in the virtual world, we then provide a brief overview of the main factors leading to cybersickness. Next, we summarize the current state of locomotion research to set the ground for our four introduced locomotion techniques in chapter 3. Finally, we introduce the effect of virtual body ownership which we extend upon in chapter 5.

2.1 Presence and Immersion

VR headsets replace the user's view with a partially realistic virtual world. Two aspects come into play to invoke the user's feeling of actually being in this virtual environment: presence and immersion. Even though both are sometimes used interchangeably, we stay in line with the majority of prior research and use the term *immersion* [24, 133] to describe the technical hardware quality of the VR system. In contrast, the term *presence* [62, 136] describes the resulting perceptual effect of being present in the virtual world.

Apart from determining how a particular experience is perceived, presence also influences how users behave in VR. In environments with high visual realism [138] that invoke a strong place and plausibility illusion [137], people generally act realistically, just as they would in the real environment. For instance, the walking trajectories when using natural walking conform to real-world walking patterns [29, 49], and users tend to walk around virtual objects [129]. These effects largely depend on the user's understanding of the virtual world, and incorrect interpretations can lead to arbitrary results [135].

Another highly relevant characteristic of VR experiences is spatial orientation, the human ability to perceive the body's orientation and position relative to the surrounding environment [171, 173]. Humans generally rely on a mixture of visual and proprioceptive cues while moving in an environment [166]. Virtual worlds tend to reduce this spatial awareness [115]. Even though the reasons are not yet fully understood, the effect is likely caused by differences in the perception of motion and environmental cues necessary for maintaining a sense of spatial orientation. In this regard, virtual locomotion techniques perform particularly badly, whereas physical walking has been shown to elicit the best spatial awareness [32].

2.2 Cybersickness

Depending on the type of virtual scenario, some users may experience discomfort when consuming VR content [64, 79]. These symptoms, similar to those when traveling in a car, are commonly referred to as cybersickness or VR sickness. Other researchers have also used the term simulator sickness [75]. However, it is essential to note that cybersickness and simulator sickness are two different branches of the overarching motion sickness phenomenon that differ in cause and effect [99, 110].

Simulator sickness [145] was mainly an issue during the first days of flight simulators and describes mild oculomotor and nausea symptoms that are caused by technical issues due to a misconfigured simulator [70]. In contrast, cybersickness causes more severe symptoms [122], including disorientation and nausea [145]. Even though the exact reasons remain a point of research with different theories being discussed, the source for cybersickness certainly lies within a mismatch of the human vestibular and visual systems [122].

In VR setups, this mismatch can be caused by various factors, ranging from technical reasons, such as a not-optimally configured eye distance of the HMD lenses, to characteristics of the virtual scenario, such as a perceived high visual flow [82]. Another phenomenon closely linked to cybersickness is vection, as suggested by Hettinger et al. [63]. This false feeling of self-movement solely induced by the visual system is not only experienced in VR but also, for example, when watching an adjacent train accelerating through the windows of the own train. Finally, the user's field of view (FOV) plays a crucial role in boosting or reducing cybersickness, as larger fields of view increase the perceived visual flow. Consequently, past research has shown that limiting the FOV can effectively reduce the experienced symptoms [48, 85].

Even though this collection raises the concern that any VR scenarios involving high amounts of visual flow and discrepancies between the observed and real movement are prone to cybersickness, recent research has also indicated that mild cybersickness does not necessarily clash with enjoyable VR experiences [164].

2.3 Locomotion

In most VR experiences, the users do not remain in a single stationary position. Instead, they can use a locomotion technique to move through the virtual world, explore the surroundings, and travel between distant locations [93, 153]. Since the early days of VR research, numerous locomotion techniques have been developed, and more than a hundred concepts are already included in the base *LocomotionVault* [36]. However, given the diversity of virtual scenarios, real environments, and personal preferences, there is not one single locomotion concept that fits every use case. Instead, researchers and developers must pick the correct approach for their particular situation. Therefore, multiple taxonomies and reviews have been proposed to structure this ample design space [2, 12, 13, 81].

One of the simplest locomotion approaches is to translate the user's steps from the physical tracking area to the virtual environment [128]. This natural walking preserves high presence and benefits the formation of a cognitive map of the surroundings [127]. Consequently, it is often favored over other locomotion techniques [2], especially if the virtual world and real environment match [150]. However, the constraints of the play area usually limit room-scale tracking to a few square meters. Even though unlimited walking can be achieved through hardware solutions, such as omnidirectional treadmills [33, 163], these devices are mostly too bulky and expensive to be a suitable approach for the broader public.

Therefore, past research has focused on developing alternative approaches. Virtual locomotion techniques achieve an unlimited range of travel by decoupling the virtual motions from the real movements. However, it is best to use only short and fast movements without acceleration [95, 181], as continuous virtual translations are known to induce cybersickness [61, 143]. A typical example of such virtual locomotion techniques is the instant teleport [20], which is used in many consumer applications. Although easy to implement and with better performance than gamepad controls [52], the concept can break the user's presence [19] and cause disorientation due to the instant relocation [14]. Also, distance estimations are worse than with real walking [6, 19]. Another concept is the *world-in-miniature* (WIM) [31, 80, 149] technique that uses a virtual three-dimensional minimap to realize instantaneous travels to any point. Compared to teleportation, WIM works better with larger distances and occlusions [8]; however, it introduces the minimap as an additional interface.

Unfortunately, virtual locomotion concepts often fail to achieve the same perceptual qualities as natural walking [161]. An alternative is gesture-based locomotion techniques. Instead of using actual steps, these concepts employ walking-related movements, such as arm swings or walking on the spot, to trick the human brain into a walking impression. This approach results in a more realistic experience and reduces adverse side effects such as cybersickness [30, 105]. The most prominent technique in this category is the *walking-in-place* [142, 156] concept, where users perform steps on the spot to mimic the natural walking pattern. However, initial implementations could not compete with real walking [161] and suffered from various drawbacks, such as warm-up phases [142], step lag [170], or hardware requirements [154]. Later research improved on the algorithms [47, 154, 180], for example, by considering gait-related biomechanics [168] and switching seamlessly between real walking and walking-in-place [9].

Additionally, many gesture-based locomotion concepts suffer from the so-called unintended positional drift (UPD) [102]. Users of such techniques tend to move subconsciously in the direction they face in VR. This effect is particularly detrimental, as walking-in-place is usually applied to counter the physical constraints of a stationary setup. Even though gradual feedback can reduce UPD [104], the safest solution is the usage of locomotion techniques where the feet stay in permanent contact with the ground [101]. This constraint is fulfilled for the concept of *arm-swinging* [92, 111, 178] and the similar approach *arm-cycling* [30]. Users determine the desired walking speed and direction by swinging their arms just like they would while walking. The concept feels more natural than walking-in-place [105], offers superior spatial orientation, and does not induce cybersickness [30]. However, poor navigation precision leads to additional repositionings to reach the intended target [15]. Additionally, this concept suffers from compatibility issues with other interactions [105]. An alternative technique is *point-tugging* [30], which resembles pulling the own body along an imaginary rope by dragging the controller backward. Even though users benefit from better spatial orientation, the motion is exhaustive and cybersickness-prone due to the view-independent movement. Hence, research suggests using the gaze direction instead of the torso direction for gesture-based travel [171].

Apart from using walking-inspired gestures for virtual locomotion techniques, another category of concepts focuses on better using the available tracking space, thus allowing users to travel larger distances by foot. Arguably the most famous representatives in this category are redirection techniques, such as redirected walking [120, 121], which unconsciously deviate the virtual locomotion from the real movements. For instance, applying a slight virtual rotation at every step causes the users to move in circles while feeling like they are walking a straight line. Later publications improved upon the concept [43, 59, 77] and refined the detection thresholds for different users and conditions [175]. Another recent work by Williams et al. [174] introduced alignment-based redirections that minimize collisions with the physical environment. For an in-depth review on redirected walking, we point to the work by Nilsson et al. [103] and Suma et al. [151]. Instead of imperceptibly changing the user's position, other concepts alter the environment overtly to achieve similar effects [134]. For example, multiple papers used portals to redirect users back to the tracking space's center [51, 86, 97] or to switch between two virtual realms [23]. However, using portals for locomotion might cause confusion and diminish spatial orientation [51].

An alternative approach for extending the available walking range is to apply translational gains that amplify the mapping between real and virtual movements [172]. Whereas this concept is already used for redirected walking, the typical gain factors are usually unnoticeably small [59, 147]. In contrast, the *Seven League Boots* concept by Interrante et al. [68] has successfully applied considerably larger gain factors to boost the user's forward movement. Similarly, Bolte et al. [14] developed a locomotion technique that scales the user's jumps to travel further. However, applying large gain factors to the virtual movements is known to cause severe cybersickness [27, 124, 155], reduce navigational accuracy, and lead to confusion if there is no clear distinction between the local and accelerated walking [176]. The reviews by Nabioyuni and Bowman [100] and Cardoso and Perotta [25] discuss these and other walking-related locomotion techniques in greater detail.

Apart from the usual travel within a typical VR world, locomotion techniques were also developed for other types of VR navigation. So-called multiscale virtual environments (MSVEs) [184] switch between distinct observation levels at different scale factors. For example, Kopper et al. [76] used MSVEs to explore human organs. For such use cases, automatic scaling outperforms manual scaling in terms of usability. Also, it is essential to calibrate the scaling speed and stereoscopic parameters automatically to avoid inducing cybersickness [4]. Another atypical type of locomotion is the transition between different scenes [96] or between the virtual environment and the real world [65, 146]. Well-designed transitions can improve the user experience by maintaining spatial perception [183], whereas abrupt cuts break the user's presence [108] by drawing attention to the virtuality of the scenario [96]. Additionally, predictable transitions are favorable for continuity, especially if they grant a preview into the next scene [67]. Another use case of transitions between different viewpoints is cinematic VR. The primary goal is to align the points of attention [16] and maintain continuity through spatial relations, such as establishing shots or eyeline matches [73]. In such cases, animated transformations are superior, as instant relocations can easily disorient and confuse users [73, 98].

2.4 Embodiment

In VR, users might develop a sensation of embodying a body different from their own. Research on this sensation originates in experiments on the illusory ownership of a fake rubber hand [18, 132]. Later research proved this effect also for whole bodies [42, 84], faces [157], and voices [185]. Perceived ownership of an artificial body can lead to various sensations, such as a drift in self-location [69] or a simultaneous identification with two distinct bodies [5, 83, 84]. Prior research has developed various models to explain the connections between external stimuli and these cognitive body perceptions [42, 84, 117, 158]. Additionally, the effect is transferrable to virtual environments [7, 140] by tracking the user's movements and using them to animate a virtual character. This process is called avatar embodiment [144] and can lead to the illusion of virtual body ownership (IVBO) [89], where users perceive the avatar as their own body.

Multiple factors contribute to the formation of IVBO. From the original experiments with a rubber hand, we know the effectiveness of synchronous visuotactile stimulations [159]. Later research revealed that sensorimotor cues are even more powerful [131, 141]. The third category of contributing factors encompasses visuoproprioceptive cues [91], such as body continuity [139], realism [3], customizability [165], or the used perspective [141]. A subset of these contributing factors can suffice to induce a feeling of IVBO [131]. However, a noticeable disruption in just one of the cues can be enough to break the illusion [74].

Even though Debara et al. [34] did not find a significant difference in body ownership between first-person and third-person views when combined with visuomotor synchrony, most prior research used a first-person perspective [91, 116, 141]. Generally, both viewing positions can elicit equally high presence and agency, but they also offer unique benefits [130]. The first-person view is best used for interaction-intensive tasks, whereas the third-person perspective improves spatial awareness and environmental perception [57]. Another disadvantage of the first-person perspective that specifically concerns embodiment is the limited visibility of the own body. This disadvantage is commonly countered by using virtual mirrors [78].

Virtual body ownership is not limited to a specific virtual body. Instead, prior research has applied the illusion to avatars of different gender [141], age [7], race [114], and body shapes [71, 106, 162]. Also, users can experience ownership of nonhuman characters [89] and transformed or additional body parts [41, 60, 72, 148, 179]. For instance, Kilteni et al. [72] could stretch the virtual arm up to four times its original length without losing IVBO. Similarly, adding a third arm preserves the IVBO sensation and induces a double-touch feeling [41, 60]. Other research has focused on nonhuman body parts, such as tails [148] or wings [40].

Apart from being an interesting psychological effect, virtual body ownership also offers various benefits to the VR application, such as boosting presence [144] and game experience [88] or improving distance estimations [123] and spatial knowledge [39, 81]. Lastly, embodiment is often connected to the so-called Proteus effect [182], which describes the unconscious projection of avatar characteristics on self-perception. Prior literature demonstrated the effect by evoking childish feelings when controlling a child avatar [7], increasing perceived strength when playing tough characters [90], or reducing the racial bias when embodying black people [114].

Measuring IVBO remains challenging, and validated questionnaires are still in the early days [38]. Gonzalez-Franco and Peck [56] condensed over 30 questionnaire-based embodiment studies into a general 25-item questionnaire, which was recently refined into a validated 16-item version [113]. Concurrently, Roth et al. [126] developed the preliminary alpha IVBO questionnaire, which culminated in the Virtual Embodiment Questionnaire (VEQ) [125]. Whereas Peck and Gonzalez-Franco focus primarily on the differences between the real and virtual body, the VEQ [125] emphasizes acceptance and agency, that is, experiencing the avatar's body and actions as one's owns. Finally, Eubanks et al. [45] also proposed a short survey for VR, which lacks a thorough validation due to COVID-19.

3 Locomotion

In the first part of this dissertation, we concentrate on locomotion to answer the question: How do we move through extensive virtual environments? Just as VR applications have different purposes, be it entertainment, education, or visualization, their environments range from the size of small rooms to entire virtual worlds spanning many square kilometers. Consequently, locomotion techniques are required to explore the world, travel between distant destinations, or reach nearby interactive elements. As we have seen in the previous section, researchers have already developed a plethora of locomotion techniques. None of these concepts suit every combination of virtual environment, physical play space, and user preference. Hence, developers must always choose the best approach for each situation.

An observant reader might ask why, if so many locomotion techniques are available, should anyone bother to design new ones. In each of our publications, we have identified a decisive gap in the literature or the possibility of improving existing concepts to allow for broader and better application. Additionally, each presented concept targets a different use case. The first three techniques rely on real walking in a room-scale setting. Two are designed for vast virtual environments [P12, P15, P17], like open landscapes, whereas the third targets confined, narrow surroundings [P4], such as city streets. The last paper [P3] focuses on stationary VR setups and combines two gesture-based locomotion concepts for fast and easy traveling.

3.1 Virtual Body Scaling

Natural walking provides significant advantages to the user experience and perceived presence [2]. Additionally, it supports forming a cognitive map of the surroundings and avoids cybersickness [127]. Nevertheless, the physical limitations of the tracking area reduce applicability to local navigation alone, which is why most VR applications fall back to virtual locomotion techniques for long-distance travel. Especially when exploring vast open VR environments, this fallback severely diminishes the positive effect of walking. With our research, we sought to fill this gap in locomotion research by developing concepts that effectively extend the available range reachable by real walking. In the spirit of exploring novel perspectives and thinking outside the box, our

Figure 3.1: With our GulliVR concept [P17], users can transform into a giant on demand and travel large virtual distances by natural walking. Players experience no cybersickness due to the proportional scaling of the eye distance.

approaches alter the normal one-to-one mapping between the virtual environment and real surroundings by enlarging the user to giant size.

It is important to note that by scaling the virtual body, every movement the users perform in the physical tracking space is scaled as well. This characteristic has multiple advantages. The concept increases the effective walking range while the physical tracking space remains the same. For instance, using a scale factor of 100, a walking distance of 2 m would translate to 200 m in VR. Besides, scaling the body increases the user's virtual stride length, thus allowing them to travel faster with the same physical speed. As we scale the whole virtual body, the view height is increased accordingly. Users tower as giants over the scene, which naturally provides a better overview of the scene. Finally, in contrast to other locomotion concepts, our resizing scales the user's eye distance accordingly. This detail is vital because it gives the impression of being a giant in a miniature world [162]. Other locomotion techniques, like flying, often suffer from cybersickness due to accelerated movements. The eye-distance scaling prevents the issue by tricking the brain into the impression of still walking with the original speed, just with a much larger body.

Our first concept using virtual body scaling is the *GulliVR* technique [P17]. Named after the *Gulliver's Travels* novel, it allows users to travel large distances by transforming into giants on demand. Therefore, users start in a traditional unscaled first-person perspective. To travel to the next target, they may initiate a switch to the enlarged "giant" mode. With a 100x larger virtual body, they can easily reach the target by walking and ultimately switching back to the original size (see Figure 3.1). Whereas the inherent concept appears straightforward, the implementational details require attention to avoid inducing discomfort, e.g., through the transition between normal and giant modes. Previous research emphasized the importance of keeping animated translations fast and short to avoid cybersickness [95, 181]. On the other hand, we aimed to emphasize the actual rescaling into the giant form to prevent users' confusion. Ultimately, we used the formula $t = 0.005 * scale$ to determine the optimal transition time.

Our primary goal with the GulliVR concept was to increase the available locomotion range of real walking while preserving its inherent benefits to presence and orientation. To confirm our assumption, we conducted a between-subject study and compared GulliVR against the predominantly used teleport technique [20]. The results confirmed that our concept significantly boosted experienced presence and led to a better understanding of the virtual world. Beside, subjects walked significantly more and did not suffer from any cybersickness. In our paper, we used these insights to discuss the resulting design implications to consider when using GulliVR in VR applications.

To summarize, our presented GulliVR technique enables the use of natural walking to explore extensive open VR environments, including all connected benefits. However, the concept comes with limitations to its practical applicability. Even though we largely increased the effective walking distance, users might eventually reach the boundaries of the physical play space. Additionally, developers must embed the scaling concept into their storytelling, as the users, as protagonists of the experience, turn into giants for traveling. Furthermore, the locomotion concept makes limiting movement in the virtual world difficult. Instead, users can reach almost any destination by simply walking there and switching back to normal mode. Finally, the travel phase takes almost no time, which confounds the impression of the traveled distance.

Our second concept, *Outstanding* [P12, P15], expands upon the original GulliVR technique and adds an innovative perspective switch. As before, users start in an unscaled first-person perspective and explore their local surroundings with real walking. For longer distances, we introduce a new travel mode. After initiating the switch, users are scaled to an enlarged third-person view (see Figure 3.2). Simultaneously, a virtual avatar is displayed at the user's feet to mark the original position in normal mode. We support the impression of disembodying the own character by adapting the original scaling from the GulliVR project. Therefore, the scaling is combined with a backward translation to achieve a comfortable 45° viewing angle on the avatar. To emphasize this transition, we use a curved dolly-shot-like animation consisting of a horizontal movement followed by a steep vertical growth. In travel mode, the users can command their avatar by setting navigation targets using raycast aiming. While the avatar walks to the set target, the users may explore the surrounding world independently, for they

Figure 3.2: Our Outstanding concept [P12] allows users to switch to an enlarged third-person perspective and control their avatar via raycast aiming. Bottom left: We finetuned the transition parameters to convey a feeling of embodying or disembodying the avatar.

are completely decoupled from the avatar's movements. At any time, the users may decide to initiate a similar transition curve to reembody their avatar and switch back to normal mode.

Our concept's design uses the two perspectives optimally to combine the individual benefits. Past research has shown that the first-person view benefits interactions, whereas the third-person perspective should be used to improve spatial awareness [57]. Additionally, we tackle the challenges of the GulliVR technique. Even though users may still use real walking in travel mode to explore the environment, this is not a requirement for navigation. Thus, our concept also works in smaller tracking spaces. Furthermore, the separation between avatar and enlarged users grants developers more control over the users' actions as they can limit where and how fast the avatar can walk.

Similar to the GulliVR project, we compared Outstanding to the teleport technique. The results of our between-subject study revealed that Outstanding maintains high levels of presence, competence, and enjoyment. It also increases spatial orientation while avoiding any cybersickness. Players generally welcomed the idea of the dynamic switching between different perspectives as a novel and fluent locomotion technique that did not cause significant problems. In the final part of our work, we condensed the study's results and additional verbal feedback into design guidelines and discussed potential extensions to our technique that further improve usability.

In summary, we established two novel locomotion concepts for large open VR environments. Both techniques benefit perceived presence and spatial orientation while avoiding cybersickness and motivating users to walk more. Of course, neither GulliVR nor Outstanding is a universal locomotion technique suitable for every situation — such a techniques might not even exist. Whereas they have shown excellent results for exploring large open VR environments, their slow tempo makes them a less-optimal choice for fast-paced experiences. Additionally, they are not well suited for exploring dense environments consisting of narrow streets or indoor areas since the virtual body scaling requires an open sky to work correctly. Lastly, the benefits to spatial orientation are likely limited to open environments granting an overlook of the surroundings.

3.2 Scaled Walking

Our Outstanding and GulliVR concepts revolve around scaling the complete users and thereby the walking speed in the virtual environment. As explained in the previous section, this idea works well for open worlds but not for close environments like narrow streets. In such cases, it would be favorable to scale the walking speed without growing the virtual body to giant size. This concept of augmenting the user's steps with translational gains has already been covered in prior literature [172]. However, just scaling the user's movements also boosts otherwise unperceived motions, such as tracking errors or walking-related head bobbing. Therefore, the probably most renowned technique, Seven League Boots [68], applies translational gains only to the user's forward movement.

Despite this improvement, several issues remain and prevent this family of locomotion techniques from being widely used. Firstly, detecting the users' intended movement direction from their actions is challenging [1, 169]. Secondly, scaling must be applied only while walking because scaling stationary head movements has been shown to cause severe cybersickness and disorientation [176]. Thirdly, substantial translational gains reduce accuracy and increase the necessary workload [28, 177]. Lastly, large gain factors increase the visual flow even when applied only in the forward direction. High visual flow is known to contribute to the formation of cybersickness. As past research has revealed a correlation between the chosen gain factor and the occurrence of cybersickness [155], other locomotion techniques rarely exceeded gain factors of 10x. Instead, Abtahi et al. [1] even suggest limiting the factor to 3x. Together, these disadvantages make scaled walking in its current form a poor locomotion choice for most use cases.

We addressed the issues by developing a novel locomotion technique for scaled walking [P4] (see Figure 3.3). Our concept prevents cybersickness, typically observed with large translational gains, by creating a space-bending illusion with virtual portals. The

Figure 3.3: Our scaled-walking concept [P4] accelerates the user's physical steps to traverse larger distances by natural walking. We prevent cybersickness by reducing the visual flow with a virtual tunnel. Windows in the walls provide a peripheral view of the scaled movement.

core element of our technique is a virtual tunnel for fast traveling along a straight route from the user's current position to a predetermined target. In contrast to comparable techniques like the Seven-League Boots [68], our design choice to concentrate on fixed straight routes prevents the loss in accuracy typically observed for large gain factors. When viewed from the outside, the tunnel appears to span all the way from the user's position to the navigation goal. However, the tunnel's interior is just a fraction as long. As the users walk through the tunnel, they get the impression of walking only the short distance from entry to exit, whereas, in reality, their forward movement is scaled so that they reach their far-away target when leaving the tunnel. For instance, in our study environment, a tunnel with a gain factor of 30x compressed a distance of 75 m to only 2.5 m.

We achieve this space-bending effect by using portals at the tunnel's ends and moving the tunnel's interior with the users as they walk through it (see Figure 3.4). This concept enables us to drastically scale the user's forward movement without risking detrimental effects. Since we limit the acceleration to the tunnel alone, deducing the user's intended movement direction is not necessary. Furthermore, we scale the movements only inside the tunnel, which minimizes the risk of accidentally applying translational gains to stationary head movements. Lastly and most importantly, the tunnel shields the users from the visual flow from scaling their movements and thereby prevents the occurrence of cybersickness.

However, the tunnel just produces a perfect "shortened tunnel" illusion in this state. Users do not receive any impression of the actually covered distance, which would

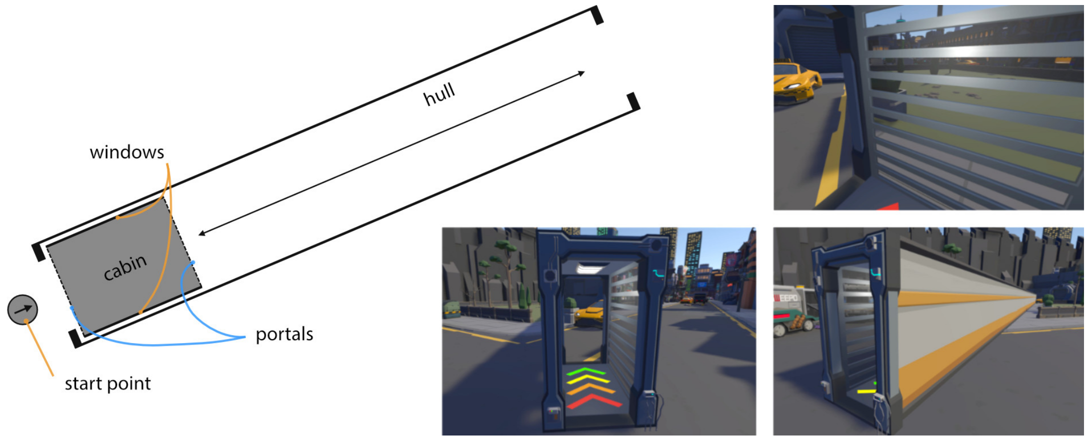

Figure 3.4: Our virtual tunnel [P4] spans from the user's start point to the target. As users traverse the cabin, it is unnoticedly moved along the tunnel. Whereas the portals create a space-bending illusion, the windows reveal the accelerated movement.

lead to disorientation upon exiting the tunnel. Hence, we added window slits to the tunnel's walls to counter this issue. These windows enable a direct peripheral view of the actual scaled movement and give users the impression of moving faster than usual. Still, the rest of the tunnel preserves its relative position to the users and serves as a visual rest frame to prevent cybersickness. We determined the optimal shape and size of the windows to carefully balance the impression of the travel movement with the shielding effect.

Altogether, our locomotion technique enables fast and easy traveling by scaling the user's steps along a straight path. We conducted a within-subject study comparing the technique against teleportation to validate our approach. We chose this comparison as the teleport can be considered the complete opposite, featuring instant and free navigation within the boundaries of the virtual world, compared to the restricted walking experience of our concept. The study's results revealed that the tunnel concept preserved high levels of presence, effectively avoided cybersickness, and increased the perceived and actual physical activity. Furthermore, the concept was found to be more beginner-friendly than the teleport. Finally, we discussed the underlying design considerations in the last part of our work, including possible extensions, such as setting the navigation target freely or choosing the correct gain factor, and limitations concerning the applicability of our approach.

To summarize, our novel locomotion concept improves significantly upon previous scaled walking techniques by enabling higher translational gain factors while diminishing major weak spots, such as the occurrence of cybersickness or the loss in accuracy.

3.3 Gesture-Based Navigation

The previous sections focused on locomotion techniques based on real walking. However, many VR setups do not offer enough space to enable room-scale tracking. Thus, navigation concepts for stationary setups are just as important. Prior research has proposed gesture-based locomotion techniques to achieve a walking-like experience while staying in one spot. Instead of walking physically, these concepts use walking-related movements to trick the human brain into a walking impression. The most prominent example in this category is walking-in-place [142, 156], where users perform steps on the spot. Compared to virtual locomotion techniques, this approach increases the feeling of movement while preventing cybersickness. However, many gesture-based concepts require additional hardware, e.g., for tracking foot movements [154, 171], and suffer from a common problem: unintended positional drift [102]. Users tend to move physically in the direction they intend to travel in VR, which is a highly problematic side effect for stationary locomotion. Prior research recommended avoiding UPD by using only techniques where the user's feet stay in contact with the ground [101].

In our work, we combined two gesture-based locomotion concepts that fall into this category but come with significant drawbacks: arm-swinging [92, 111] and point-tugging [30] (see Figure 3.5). When using arm-swinging, users swing their arms in a smooth motion just like they would during a walk. The algorithm extracts the desired walking direction and speed from these swings. Whereas this technique reportedly feels natural, does not cause cybersickness, and is less exhaustive than traditional walking-in-place [105], it suffers from overall poor navigational precision [15]. Consequently, the technique is better suited for long travels and should be accomplished with another concept for local maneuvering. The second technique, point-tugging, resembles tugging oneself along an invisible rope. The users stretch their arms in front of them, press a button on the controller and pull themselves forward while dragging their arms back. This concept allows for precise, omnidirectional movements but is usually too tedious for long travels, leading to fatigue and cybersickness [30]. Thus, it is better suited for local maneuvering than for long-distance travel.

Given these complementary characteristics, we combined both concepts into a single locomotion technique to leverage the individual strengths: *Tug & Swing* [P3]. Our approach primarily consists of two distinct states. Raising the arms to chest height allows users to use point-tugging for local maneuvering. In contrast, arm-swinging is activated by lowering the controllers to the waist level. This automatic switch based on the controller height is inspired by our natural arm posture. Typically, many objects in virtual environments are located at chest height to ease interaction. Thus, we usually lift our arms higher when interacting with these objects. In turn, most people lower

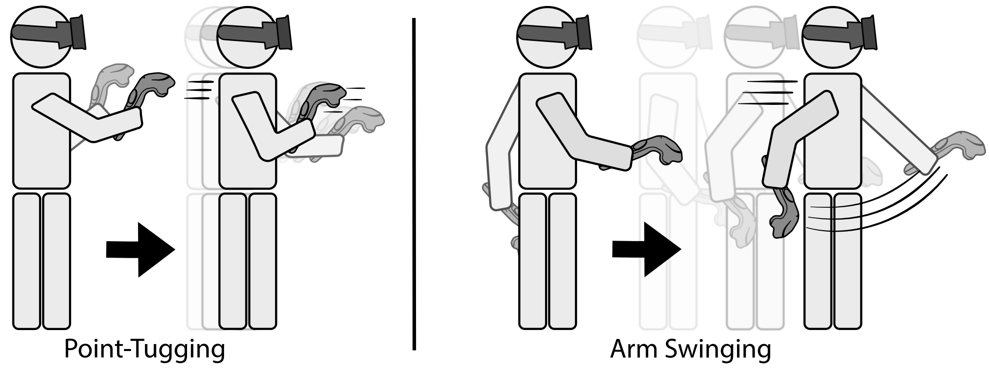

Figure 3.5: Our Tug & Swing concept [P3] combines two established locomotion techniques. Left: users perform point-tugging at chest height for local maneuvering. Right: swinging the arms at waist level activates an accelerated forward motion for long-distance travel.

their arms around waist height while walking. By incorporating these observations into our locomotion technique, we aimed to reduce the necessary cognitive workload.

In addition to the seamless transition between both modes, we adapted the original arm-swinging implementation to make traveling faster and smoother. Firstly, we accelerate the forward movement depending on the arm-swinging velocity. Swinging faster allows for further traveling with each swing. After evaluating the applied parameters in an iterative design process, we added a minimal threshold velocity from which the boost is applied and capped the maximal boost factor to avoid unintended movements. The final boost factor is calculated according to the following formula:

$$boost_{forward} = \begin{cases} 1.0 & \text{if } v_c \leq 1\,m/s \\ 5.0 & \text{if } v_c \geq 3\,m/s \\ 2\,v_c - 1 & \text{otherwise} \end{cases}$$

Next, we did not use the direction of the arm-swings to determine the intended travel direction. Instead, research has shown that using the headset's direction leads to improved spatial orientation and reduced cybersickness [171]. Additionally, we smooth the forward direction over multiple frames to reduce head-bobbing artifacts. Lastly, instead of using continuous swings, users must activate each swing by pressing the controller's trigger in front of their body before swinging the arm backward and releasing the button. Even though this design requires a short adaption phase, it matches the point-tugging controls and ultimately reduces the complexity of the composite technique even further. All three modifications apply only to the arm-swinging mode, as point-tugging should provide unconstrained local maneuvering in all directions. However, for longer distances, these adaptations reduce the necessary mental workload and ensure predictable movements.

As with the previous locomotion techniques, we validated our novel concept in a within-subject study against the teleport. In this case, the choice for the teleport was motivated by the comparability to previous studies covering the original implementations [15, 30]. Our results confirmed that the subjects could navigate the virtual environment effectively using our combined approach without experiencing notable cybersickness symptoms. Additionally, subjects felt more active and reported significantly higher levels of perceived presence. However, our gesture-based approach is also more challenging and increases the required travel time and physical effort. Nevertheless, subjects mostly welcomed these aspects and emphasized the experienced realism.

In summary, our presented Tug & Swing concept successfully improves upon the two locomotion techniques, arm-swinging and point-tugging, to combine the individual strengths into a cohesive travel experience. Even though this technique is not suited for every situation, it is a valuable addition to the category of stationary locomotion concepts, promising a walking-like experience with high presence levels without causing cybersickness.

3.4 Recap on Locomotion

In this chapter, we presented four novel locomotion techniques that target a wide range of settings, ranging from stationary setups to large, open VR environments. In all cases, we highly prioritized providing a good user experience, avoiding cybersickness, and giving a comprehensive impression of the virtual world. Additionally, the concepts should blend into the virtual environment and not interrupt the users' presence. Instead of aiming for maximal realism, our techniques were designed to feel as natural as possible in VR. Consequently, some of our devised core aspects, such as the perspective switch or the space-bending tunnel, do not have a real-world counterpart but are based solely on the unique characteristics of immersive VR experiences. Nevertheless, our results revealed that this design approach offers a range of decisive benefits and can even increase the perceived realism of the virtual world. Of course, our locomotion techniques are not one-size-fits-all solutions for all applications. However, we are confident that our work is a major advancement in locomotion research and inspires future research on these promising concepts. Additionally, the results motivate us to extend on such VR-first interaction concepts to leverage the full potential of VR experiences.

4 Interaction

After contributing novel and intuitive locomotion techniques to explore large virtual worlds, we dedicate this chapter to the interaction within the VR environment. Except for pure visualization use cases, every VR application requires input modalities that allow users to interact with the elements in the virtual world. However, existing interaction concepts are not easily transferable from non-VR experiences. Using traditional interfaces introduces new challenges, such as an occlusion-free placement of the interface or the intersection of a 3D pointer on a two-dimensional (2D) surface. Also, users experience the virtual environment as a substitute for reality, leading to an increased sensitivity for incoherent and unnatural interactions. Instead, VR applications can greatly benefit from developing intuitive, VR-first interaction concepts that leverage its unique capabilities and enhance the feeling of being present in the virtual world.

This chapter covers three vital areas of interaction research: understanding user behavior, imagining novel input modalities, and structuring interface design. First, we investigate how users behave in a virtual environment they know is not physically real. In order to design meaningful experiences that achieve the intended effect on the users, developers must be confident that the users behave as expected. Therefore, we investigate the effect of virtual walls on the users' walking patterns when performing interaction-intensive tasks in VR [P6]. Next, we challenge the established interaction patterns that are mostly dominated by hand and controller inputs. Therefore, we explore the potential of novel gait-related input modalities on the example of sneaking in a stealth game [P9]. Finally, we focus on designing user interfaces specifically for immersive scenarios. In our work [P7, P11], we investigate the design space of storage interfaces for VR and condense our insights into a structural taxonomy for such inventories.

4.1 Movement Behavior in Virtual Environments

The majority of our presented locomotion techniques in the first chapter revolve around real walking via room-scale tracking. However, most play spaces do not conform in size and shape to the virtual world. This deviation between physical surroundings and

VR scenario is an ever-present issue when designing immersive VR experience that manifests in two potential problems: Firstly, walls in virtual environments mostly do not have a physical counterpart, and users might accidentally or willingly ignore them. The absence of subsequent collisions breaks the coherence of the simulation and draws the users' attention to the virtuality of the scene, which can easily interrupt the users' presence [11]. Secondly, obstacles in the physical room are usually invisible in VR, and dangerous collisions are prevented by marking the play space's borders with clearly identifiable walls. If users ignored these walls, they would risk an imminent danger of injury [135].

In both cases, developers must rely on users to respect the rules of the virtual world and refrain from walking through obstacles — be it out of curiosity or in an attempt to cut short. Even though prior research has already explored various types of visual, auditory, and vibrotactile collision feedback [10, 11], little work has been done to investigate the reasons that cause users to not adhere to the virtual world's rules. Additionally, the current state of research is ambiguous. Few studies suggested that users ignore virtual obstacles under specific circumstances [11, 109], but they mainly focused on simple setups and repeating tasks, such as walking between checkpoints. In contrast, other work indicated that users generally conform to the rules in highly immersive experiences [137]. In sum, it remains unclear which specific circumstances lead to the respective observed behavior.

In our work [P6], we addressed this gap in the literature by exploring the influence of different task types and wall appearances on user behavior. Therefore, we conducted a mixed study setup to isolate the observed effects. For the between-subject part, the 40 subjects were randomly split into four groups, each being confronted with a different wall type. The four used wall designs varied in opacity and degrees of realism (see Figure 4.1). Specifically, we used two abstract walls consisting of uniform colored cuboids with 30% and 60% opacity. The two other walls matched the surrounding scenario and had the form of a fully opaque wood wall and a twine hedge with see-through holes.

Aside from the four wall designs, we also included a within-subject aspect consisting of two sequential gameplay rounds. In each round, subjects had to carry objects between different checkpoints. Usually, the direct path between these points was blocked by a wall, forcing subjects to decide whether to walk around it or cut short. To determine the influence of the task type, we varied the inherent motivation. In one round, subjects had to solve a puzzle by placing different objects in the correct spot to receive the next object and advance with the task. For instance, after using a key to unlock a chest, subjects were rewarded with a pearl that had to be put into an open shell. The other round did not offer a similar motive but was designed as a dull and repetitive job.

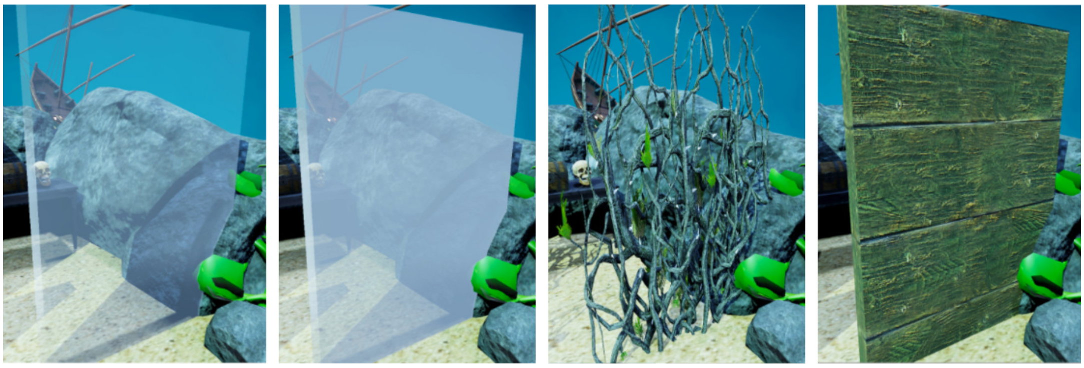

Figure 4.1: We investigated how virtual wall designs influence the users' behavior [P6]. From left to right: our study compared two abstract cuboids with 30% and 60% opacity and two realistic walls: a twine hedge with holes and an opaque wood wall.

Subjects had to carry a coin in counter-clockwise rotation from one interaction point to the other. Whereas this task resembled the first one regarding movement patterns, it was deliberately designed to feel utterly annoying.

Our study revealed that the particular task type influences the behavior the most. Whereas only very few subjects collided with one wall at most in the puzzle level, significantly more subjects ignored walls in the repetitive round to finish their task faster. We explain this finding by the participants' strong incentive to stick to realistic behavior, which is ultimately suppressed by the tedious task. Apart from this strong finding, our study also indicated that opaque surfaces are highly efficient in discouraging subjects from walking through walls as they cannot see behind them before walking through. Even though our realistic wall designs positively impacted the perceived presence, we did not find a significant effect on the measured walking behavior. In sum, users generally want to adhere to the virtual environment's rules unless they experience a strong incentive, e.g., through a repetitive task. In such cases, opaque obstacles proved to be effective countermeasures.

4.2 Designing a Gait-Related Input Modality

After investigating how users behave in the virtual world, the next step is to extend the established interaction patterns that are used in most VR applications. Even though these experiences try to let us feel utterly present in the virtual world, interaction is limited primarily to controller inputs. This limitation contradicts reality, where we use our entire body to interact with the world around us. Consequently, we argue that such interaction concepts disregard the vast potential of body-based input modalities.

Figure 4.2: We explored the potential of sneaking as a novel input modality for immersive virtual environments [P9]. With our three presented sneaking concepts, players must not only hide from the guard's view but also pay attention to their own gait to avoid detection.

Our work targets this research field by exploring the potential of gait-related input modalities for VR experiences. Our concrete example is the detection of sneaking to enhance the user experience in stealth VR games. We believe this use case is ideally suited for demonstrating the importance of extending the interaction fidelity to increase engagement and realism for VR applications.

Despite being a popular genre, many stealth games, such as Espire 1: VR Operative [37], do not offer a walking-based sneaking mechanism. Instead, players must use virtual locomotion and activate a binary sneak mode using hardware buttons. In most cases, only the direct line of sight between enemies and player is relevant, leaving one of the central aspects of sneaking vacant: being quiet. Even though we usually do not pay attention to our own footsteps, every single step emits noise that carries a range of information on position, walking speed, posture, or even emotional state [54, 112]. Besides staying out of sight, successful sneaking also requires minimizing the user's own walking sounds to avoid transmitting this information to the observant guard. On the other hand, one may also use sounds, such as stomping, deliberately to attract attention. Consequently, we argue that this interaction fidelity, which is still missing in today's VR games, could greatly benefit immersive VR experiences.

With our research [P9], we explored the potential of using sneaking as a novel input modality (see Figure 4.2). Therefore, we started with an exploratory design process to determine the best technical approach for capturing the users' sneaking behavior. In the end, we decided on three implementations that differ in tracking precision. The first concept uses ankle-attached hardware trackers [66] measuring the foot's deceleration upon impact with the ground to determine whether the users are sneaking. The second approach requires only the default hardware and uses the HMD's movement speed as a proxy for the sneaking behavior: moving slower than a predetermined threshold is considered sneaking. In contrast to the first concept, the individual footsteps are not captured. As our baseline condition, we added a third technique that is derived from existing VR games and uses joystick locomotion and a button-controlled sneak mode that limits the virtual walking speed. We selected these three techniques to determine the effect of tracking fidelity on user experience and explore the potential of using these input modalities in a stealth VR game.

Therefore, we dedicated the second part of our research to designing various interaction concepts and gameplay elements that utilize our stealth mechanisms. Combining sneaking with other time- or body-based tasks allows us to modify the overall task difficulty and provide varied challenges. Finally, we used the developed interaction concepts to compare our three sneaking mechanisms in a between-subject study. Our study's results revealed that the subjects generally appreciated the novelty of sneaking-based gameplay. Compared to the gamepad condition, our two gait-oriented mechanisms increased the perceived presence, tension, challenge, and physical activity without overcharging or exhausting the subjects. However, both approaches performed similarly, even though only the tracker-based concept precisely measured the subjects' sneaking behavior. We explain this finding by observing that subjects generally associated sneaking with walking slowly and therefore did not notice the increased tracking fidelity. We conclude that precisely tracking individual footsteps is unnecessary for our particular use case. Instead, the more abstract approach benefits the user experience more by focusing on the user's intention and providing better comprehensible feedback.

In sum, our research demonstrates the potential of using more than just the controller input for interacting with the virtual world. Integrating full-body controls and passive cues such as the users' gait can enrich the immersive experience by providing novel challenges and boosting presence and enjoyment. Furthermore, we learned that users are less sensible to imprecisions as long as the effect matches the users' expectations. Consequently, gait-related input modalities for VR games do not require the same interaction fidelity known from controller input. However, our proposed accurate footstep tracking is still promising for other use-cases, such as training physical activities like dancing or jumping with personalized feedback.

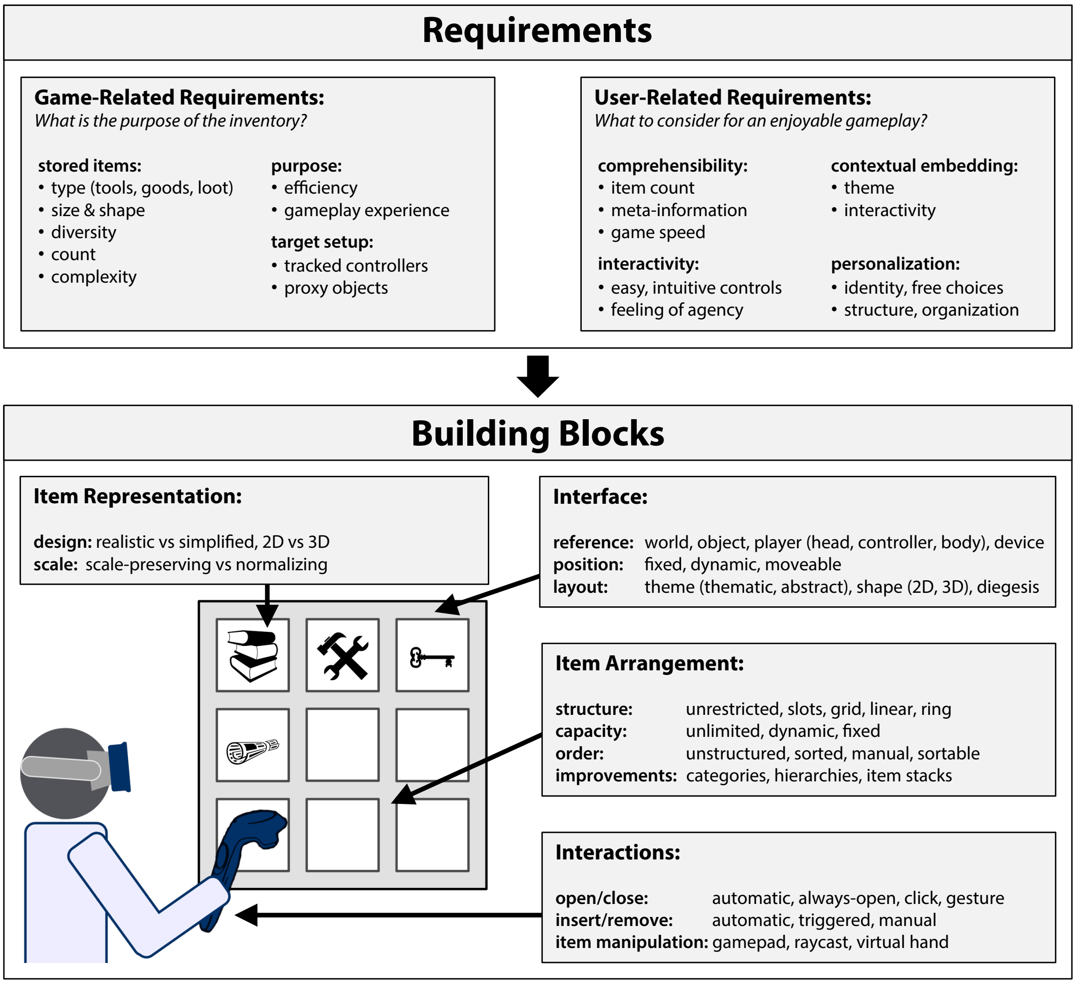

Figure 4.3: We analyzed VR games and condensed our insights concerning inventory design into a framework, comprising the requirements we should consider before designing inventories (top) and the taxonomy of available design choices (bottom) [P7].

4.3 Storage Interfaces for VR Games

Novel interaction concepts like body-based sneaking are a big step toward realistic and immersive VR experiences. However, as VR applications increase in complexity, they also require user interfaces to display, store, and modify information necessary for the application's plot. One common type of such interfaces is an inventory [167] used to store items and tools that are repeatedly needed throughout the experience. Adding an inventory to their application opens new possibilities for developers. The inventory can be used to preserve the user's progress by storing collected items, add new gameplay elements by forcing users to maintain a structured collection of their possessions, and even allow them to personalize their experience. Considering that inventories are vital for object interaction in many non-VR games, they provide a compelling addition to

Figure 4.4: Our three inventory prototypes [P7]. Flat Grid (left): 2D overlay accessed by ray-cast pointers. Virtual Drawers (middle): natural interaction with items; item scales normalized. Magnetic Surface (right): items can be positioned freely on a sticky floating surface.

the VR experience. However, most VR developers still refrain from using inventories and thus fail to reach their application's full potential and profundity.

The challenges that need to be addressed to achieve an intuitive inventory implementation are plentiful and mainly result from the unique characteristics of the VR platform. In contrast to desktop applications, VR experiences impose additional requirements, such as placing the interface in the user's sight without obstructing the surrounding. Additionally, most prior research on VR menus is not fully applicable to inventories as it does not account for the unique interactions, such as transferring a virtual object from the 3D world to the local storage interface. The discrepancy between these challenges and the potential benefit of using inventory systems in complex VR experiences provides a strong motivation for focused research on VR inventory design.

Our research goal was to form a foundation for this novel research area that comprises the current status quo, imminent design-related challenges, and future research directions. Therefore, we structured our work into three segments [P7, P11]. First, we used a literature review, in-depth developer interviews, and a grounded theory analysis [55] of inventories in current VR games to assess the current state of the art. Next, we combined these three parts into a unified framework, encompassing user- and game-related requirements and a structural taxonomy that summarizes the essential building blocks of inventory designs (see Figure 4.3). Finally, we also demonstrated the practical use of our work in action. Therefore, we used the presented framework to design three inherently different inventories: *Flat Grid*, *Virtual Drawers*, and *Magnetic Surface* (see Figure 4.4). With the help of these examples, we explained the underlying design process and discussed the remaining open questions.

With our work, we have contributed to the field of VR interaction research by providing an overview of the current state of inventory design. Our results, the taxonomy and the connected design requirements, provide a valuable guideline for researchers and practitioners. Nevertheless, we see an urgent need for further research. In particular, the connections between the various requirements and the design choices, as well as the interplay between the different building blocks, remain to be investigated. Future research will help to advance this understanding and thereby assist developers in their design process.

4.4 Recap on Interaction

This chapter covered a wide variety of areas. First, we learned that users generally conform to the rules in a virtual environment if the experience is not already spoiled, e.g., by a dull and repetitive task. Next, we presented our novel sneaking-based input modality and investigated how users perceive different levels of tracking precision. Finally, we structured the ample design space of inventories for VR games and derived a structural guideline for developers and researchers. Even though these topics differ greatly in the target domain and research methodology, all three are inspired by our inherent motivation: With our contributions, we work on enhancing the overall VR experience. However, we do not aim for more powerful hardware, better visuals, or perfect realism. Instead, our research goal is to create experiences that feel entirely natural and fluent. In this chapter, we have focused on interactions in the virtual world, whereas in the next part, we alter the user's perspective and identity in VR.

5 Perspectives

In the last chapter, we already explored stealth VR games where players become a spy and infiltrate a secret base. A unique strength of VR is that it allows users to experience otherwise impossible scenarios and increase immersion over the usual degree. One central aspect of this experience is the sensation of assuming a different role from the user's own real personality. This role may be explicitly imposed by providing a concrete backstory or implicitly indicated, for example, through the user's abilities in the virtual world. Arguably the most potent way is representing the virtual identity with an avatar. The so-called avatar embodiment [144] can ultimately lead to the perceptional phenomenon known as the illusion of virtual body ownership (IVBO) [89], where users perceive the virtual representation as their own body. This experience not only can increase presence [144] and improve distance perception [123] but also even unconsciously change the user's behavior and attitude [7, 114]. However, in most cases, researchers and developers have focused on eliciting IVBO for only one single human avatar.

In this chapter, we challenge this traditional perspective by extending the sensation of owning a different body in two novel directions. First, we explore how body ownership can also be induced for nonhumanoid avatars. Therefore, we introduce control mechanisms allowing users to embody various animals [P14, P16], such as spiders or tigers. Additionally, we examine how these techniques can be integrated into engaging experiences on the example of escape room games [P13]. In the second part, we break with the habit of undergoing a VR experience from a single point of view. In particular, we investigate the potential of multiprotagonist narratives for VR storytelling and explore transition concepts for switching between different playable characters within a continuous VR session [P2].

5.1 Animal Embodiment

Game developers are often pioneers in exploring novel mechanisms and sensations. Gamers may assume the role of the story's hero or foe; they can play as a wizard, warrior, or thief. However, even the most exotic character choices are usually limited to a humanoid representation. Especially in VR games, playable animal avatars are limited to a few exceptions, such as Eagle Flight [160]. We argue that embodying animals in VR applications offers great potential by providing a unique experience that challenges our established view of the world. Additionally, the animals' unique abilities can be used to develop novel game mechanisms such as flying as a bird or crawling as a spider. Apart from games, animal embodiment can also be helpful in biological education by allowing students to experience the world through the eyes of a creature. Similarly, this sensation can also increase our alertness for the importance of conservation measures.

5.1.1 The Illusion of Animal Body Ownership

We dedicate the first part of our research [P14, P16] to investigating if and how body ownership for animal avatars can be invoked. Even though prior research has confirmed that IVBO extends to other body shapes [72, 106] and additional body parts [40, 148], such as limbs, tails, or wings, the effect has not yet been applied to entire virtual creatures.

The main challenges when it comes to inducing body ownership for nonhumanoid characters are the divergent body proportions and postures. Whereas multiple factors contribute to IVBO, VR experiences mainly utilize sensorimotor cues, i.e., the synchronous mapping of the user's body movements onto the avatar. However, this mapping is challenging for animal characters with highly disparate body shapes. For instance, quadrupeds like tigers have the same number of limbs as humans, but their limb-to-torso ratio differs significantly, and they walk naturally on all fours. The increased limb counts of anthropods, like spiders, pose an even greater challenge. Therefore, we developed various control mechanisms to account for these different body shapes and evaluated the individual qualities with three exemplary animals that differ in shape, skeleton, and posture: bat, tiger, and spider (see Figure 5.1).

Full-Body Mapping (First-Person Perspective). This control mechanism is the closest analogy to what most people expect when playing as an animal. The users imitate the animal's posture, and their movements are exactly mapped to the virtual body using hardware trackers for the hip and legs [66]. For example, the subjects must crouch on the floor with their four limbs being mapped to the tiger's body. More complex animals, like the spider, can be achieved by simulating the additional limb movements based on the user's leg motions.

Half-Body Mapping (First-Person Perspective). Even though the full-body mapping matches the animals' posture optimally, longer sessions of crouching on the floor can be rather exhausting. Thus, we developed an alternative approach that maps only the

Figure 5.1: We investigated if users experience ownership of animal avatars [P14]. Therefore, we selected three animals with different postures (tiger), skeletons (spider), and shapes (bat) and compared them against a human avatar.

user's lower body to the animal, allowing users to remain in an upright position. For instance, each human leg is now mapped onto two tiger pawns or four spider legs. This approach minimizes the necessary physical effort while preserving a comparable amount of sensory feedback.

Third-Person Perspective. Prior research [91, 116, 141] indicated that the first-person perspective is favorable for invoking IVBO. We decided to also consider third-person mappings in our work since they allow users to see their avatar without requiring a mirror. However, the third-person perspective is challenging when users rotate around themselves. We explored three possible solutions. The first concept is often used in non-VR games and works by rotating the camera around the avatar to maintain an over-the-shoulder viewpoint. Since rotating the camera effectively means rotating and translating the user in the VR environment, this approach is associated with increased levels of cybersickness. The alternative concept is moving the avatar around the user as the rotational center. However, simply sliding the animal sideways around the user lacks realism. Therefore, in our last alternative, an intelligent agent controls the avatar by trying to maintain a natural position ahead of the user.

To evaluate the effects of the five control modes on IVBO for the three investigated animals, we conducted a within-subject study and measured the alpha IVBO questionnaire for every condition. Our results showed that even the spider offered a similar degree of IVBO compared to humanoid avatars, despite having a completely different skeleton. In some cases, the animal avatars even outperformed our baseline humanoid avatar regarding IVBO. As expected, the first-person concepts surpassed the third-person approaches significantly. The insignificant differences between the first-person implementations led us to conclude that half-body mapping is a good trade-off between fatigue and body ownership for nonupright animals. Finally, many players expressed their desire to use the animal's abilities, such as flying.

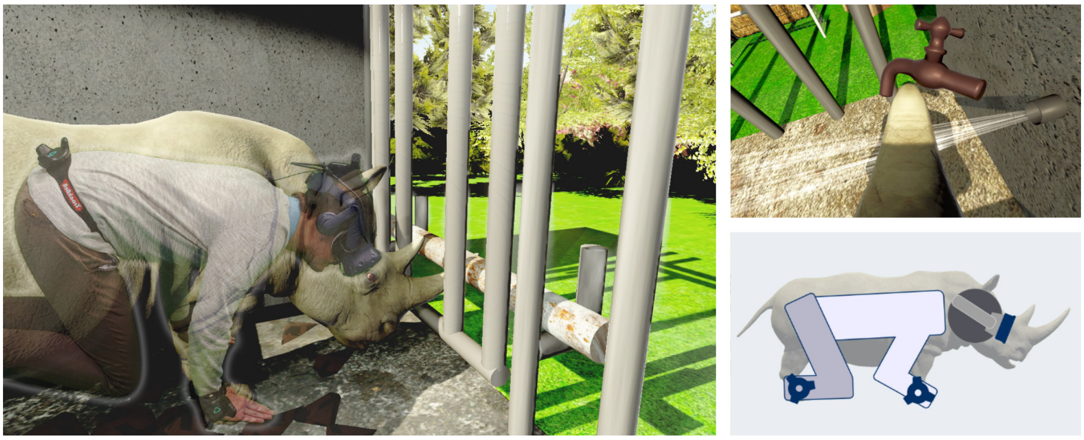

Figure 5.2: We developed three escape rooms to explore how animal avatars can be embedded in VR games [P13]. Playing as a Rhino, users had to mimic the correct posture and use the horn for unique interactions to escape from a burning zoo.

5.1.2 Using Nonhuman Avatars in VR Games

In the second part of our research [P13], we build on the findings from our first study to explore the design space of using animal avatars in VR games. Even though our initial study has confirmed that animal avatars can invoke IVBO, using these insights to design engaging VR experiences is not trivial. Due to the novelty of this research topic, there are neither focused studies on animal embodiment nor design guidelines that help developers estimate how users will perceive this experience. Consequently, we need further research to understand the benefits and challenges of using animal characters in VR games.

In particular, our publication makes two contributions. First, we explore how animal avatars can be embedded in VR games. As animals vary significantly in posture and skeleton, the generalizability of such research is limited. Therefore, we focus on a few distinct species - rhino, bird, and scorpion - and provide detailed insights into how such avatars can be used in a gaming context. For this purpose, we present three separate escape room games that combine one animal with a different control mechanism and a superhuman skill typical for this species. The rhino offers unique head-centered interactions by using its signature horn to remove a lock through the bars of its cage (see Figure 5.2). The scorpion features pincers to cut branches blocking the path and a tail to pick up and throw objects. Finally, the bird can use its wings to fly upwards and create wind gusts to interact with objects (see Figure 5.3).

Apart from discussing the design implications we learned from our game design process, our work also comprises a within-subject study to evaluate the three games regarding player experience and body ownership. Our results support our initial assumption that

Figure 5.3: The second game (left) featured a scorpion with pincers to cut through branches and a tail to throw objects. In the third game (right), users embodied a bird and had to escape from their cage by using their virtual wings to fly and create wind gusts [P13].

games created around animal avatars can lead to great enjoyment. In particular, the subjects liked the interactions with the additional body parts, such as the horn and the wings, and had no problems learning these new controls. Hence, we emphasize the importance of focusing on the animals' unique abilities during game design. Instead of sticking to the tried-and-tested concepts, we encourage developers to experiment with exotic species to create novel and engaging experiences.

Additionally, our study revealed a correlation between IVBO, perceived presence, and overall game enjoyment. Even though our research's main priority was to investigate the general potential of using animal avatars in VR games, we suggest a closer look at the causative relations of this correlation in future research. Also, the potential use cases of animal body ownership go beyond games. For example, it could be used to communicate the importance of ecological measures, increase our empathy for animals, or reduce animal-related anxieties. Finally, our results demonstrate the importance of avatar embodiment for the game experience in general. The sensation of owning a virtual body can deepen our engagement with the virtual scenario, increase presence and enjoyment, and even challenge our limited perspective on the world. Thus, in our next research project, we used our knowledge of the IVBO effect on another little-explored topic: multiprotagonist narratives.

Figure 5.4: We explored the design of in-scene transitions for switching dynamically between player characters in VR games [P2]. Apart from analyzing existing multiprotagonist titles, we presented two transition concepts, one of which used our Outstanding locomotion concept.

5.2 Character Transitions for VR Storytelling

Besides enabling novel game mechanics, avatar embodiment can also increase our engagement with the VR experience. This benefit is especially valuable for immersive storytelling. Stories play a huge part in our lives. They permit us to experience the world from different perspectives and thereby challenge our limited point of view [137]. Games, and in particular VR games, provide unmatched storytelling capabilities by providing direct control of the protagonist's actions. This interactivity fosters identification and engagement with the plot. Experiencing a sensation of body ownership toward the virtual avatar further reinforces this effect and increases the potential impact of interactive narratives in VR.

Nowadays, many games no longer tell their story from a single point of view. Instead, switching between multiple playable characters throughout the game has become a frequent theme. These narrative concepts, adopted from cinematic storytelling techniques like network plots [124] or ensemble films [6], increase perspective-taking and lead to a better understanding of the protagonists' motive forces and decisional backgrounds. Unfortunately, this positive development usually does not extend to virtual experiences. In the first part of our research, we searched for VR games featuring multiprotagonist plots. Despite evaluating 986 distinct titles, we identified only 18 fitting VR games. Considering the promising benefits of combining the superior immersive effect of virtual environments with the power of multiperspective storytelling, we see great unused potential and the need for further research.

One hurdle for the broader application of multiprotagonist plots in VR games is the design of intuitive and pleasant transitions between the different playable characters. Besides inducing cybersickness through artificial movements, improper transitions are likely to interrupt the game's flow or cause disorientation. In our publication [P2], we approach this challenging topic of designing immersive character transitions through multiple research steps. Therefore, we started by analyzing the identified 18 multiprotagonist VR games and structuring the different transition types and designs into three categories:

1. In-Scene Transitions. Games in this category feature multiple playable characters located in the same environment. However, only three titles permit players to switch freely between these protagonists by using a brief animation that changes the players' viewpoint where necessary. In contrast to giving the players complete control over the transition, three other games automatically invoke short fades or loading screens to switch from one character to the next.

2. Chapter-Based Stories. The three games that fall into this category separate the different characters into multiple chapters. Even though an overarching main plot connects the protagonists' stories, the individual levels are limited to only one playable character.

3. Multiperspective Gameplay. The biggest group comprises nine games that allow players to control two characters simultaneously. This mechanism is achieved in two ways. In most games, both protagonists share the same environment and are aware of each other, for example, by combining a third-person protagonist with an assistive first-person ally. Alternatively, some games split the environment into multiple layers, such as having the main protagonists control a secondary video game character on a virtual console.

Even though multiperspective gameplay is the most common technique in our sample, its potential for complex multiprotagonist plots is minimal. The simultaneous control of a first-person avatar and a third-person character does not work well for genres requiring ownership and identification with multiple characters of equal importance. Similarly, the chapter-based story design is more geared toward separated storylines than frequent character transitions, which are necessary for switching between group members in a continuous plot. Instead, our research focussed on in-scene transitions that form the basis for complex multidimensional stories (see Figure 5.4).

Therefore, we established a set of comprehensible design goals characterizing proper character transitions and presented two example transition concepts (see Figure 5.5). The first technique combines frequent elements from the analyzed titles. It pauses the game and displays an interface indicating the next character and their position in the

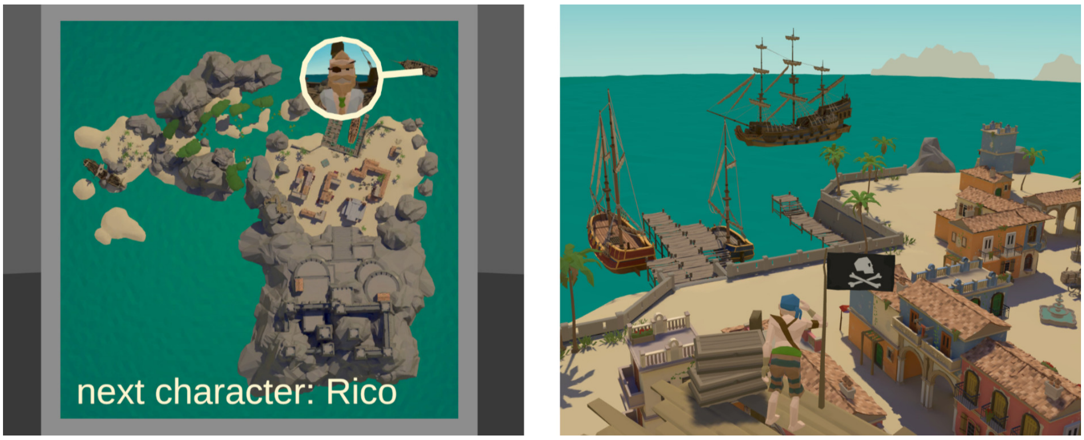

Figure 5.5: We compared two character transition concepts [P2]. The left approach pauses the game and displays a map with the next character and location. The right concept switches to a scaled third-person view before applying a quick forward translation to the next location.

world. For the second concept, we combined our published Outstanding locomotion technique [P12] with an automatic forward translation to achieve a fluent transition. In Chapter 3, we discussed that Outstanding increased presence and spatial orientation. Additionally, subjects characterized their relation to the avatar as a more distant protector-protégé-relationship in travel mode and described a feeling of possessing the avatar when switching to normal mode. We argue that these characteristics perfectly align with the goals of a character transition. Unlike the first concept, the animated transition works without any visible cut. Also, the elevated view height in travel mode provides an improved overview of the characters and their surroundings without requiring a map or interface. Finally, the perceived disembodiment of the former avatar and possessing the next protagonist facilitate perspective-taking.

With these exemplary concepts, we explored the potential of in-scene transitions for narrative VR games, identified open challenges, and revealed future research directions. In particular, we evaluated how both concepts change the players' perception of the character transitions by conducting an exploratory between-subject study. The results confirmed that the subjects generally welcome using more than one player character in a game. Also, the Outstanding-inspired concept performed better regarding spatial orientation, experienced realism, and body ownership, but neither technique caused significant cybersickness symptoms. Despite these promising findings, the participants' feedback also revealed weaknesses in both concepts, such as the missing freedom of controlling the transitions manually. Consequently, we see great potential for further improvements and the necessity for future research.

In summary, our work introduces the novel but vital research field of creating engaging multiprotagonist narratives for VR games. By telling stories from multiple perspectives, we not only can deepen the player's connection and involvement with the plot but also encourage them to widen their point of view and enhance their perspective-taking skills in real life. In times when more and more people encapsulate themselves in a bubble and block opposing views, we consider such narrative content more valuable than ever before. Thus, we are confident that our work will spark further research and assist developers in realizing immersive character transitions for future narrative VR games.

5.3 Recap on Perspectives

In this chapter, we experimented with the sensation of virtual body ownership by applying it to two new research directions: animal avatars and multiprotagonist narratives. Both projects follow our central research motivation to envision novel interactions that are possible only in VR. Whereas we believe that such experiences demonstrate the transformative power of VR, we also have to consider the technical challenges that hinder a wider adoption. For our character transitions, we tracked only the controllers and HMD while emulating the lower body. This design permitted us to use the Meta Quest 2 [46] as a widely available target platform for our study. In contrast, full-body tracking is currently possible only with specialized hardware, such as Vive Trackers [66]. Hence, our nonhuman embodiment concepts mainly remain a research topic for now. However, as technology progresses and new headsets with out-of-the-box body tracking are developed, such experiences could open an entirely new range of use cases for immersive VR. The main priority of our research is always on designing and improving interaction concepts and less on practical use in commercial software. Nevertheless, applicability should always be considered in the design process to avoid creating techniques that are not of any practical use. Therefore, we focus on two application-centered topics in our next chapter.

6 Applications

In the previous chapters, we looked at various ways of interacting with the VR world and experiencing novel sensations. This ongoing effort to improve the virtual experience itself is important. However, at the same time, we must not lose sight of the practical applicability for consumer experiences. Ultimately, VR applications will be used only if they align with the consumers' needs and expectations. Improvements in this field mainly manifest in two directions. Firstly, we must actively work on resolving the remaining barriers and weak spots of current VR setups. Secondly, efforts should be concentrated on use cases where VR can actually improve on the status quo by streamlining procedures or even enabling them in the first place.

In this chapter, we contribute to the topic with two projects. First, we focus on an ever-lasting problem of headset-based VR setup: How can external spectators watch the user's experience in the virtual world without wearing HMDs themselves? We investigate potential solutions for streamed content [P8] and physical bystanders [P10] in two publications. In the second part, we explore the potential of VR experiences for physical training. Therefore, we investigate how full-body exercises can be incorporated into VR exergames on the example of vertical jump training [P1, P5].

6.1 VR Spectatorship

The core device of every immersive VR setup is the head-mounted display, which replaces the user's view with an artificial environment. For maximal immersion, it is essential to block as much information from the physical surroundings as possible. However, this disconnection between VR users and their real surroundings is disadvantageous when they want to share their experience with a non-VR audience. In most cases, the default approach of VR applications is to mirror the user's view on a connected monitor or phone screen. As this view might not yield an optimal impression of the experience, we explored alternatives for VR spectatorship. In the first publication, we investigated how the spectators' perspective on the player changes the viewing experience for different VR games. For our second paper, we designed a novel mirror device that permits local bystanders to watch the player's actions in the virtual world while controlling their viewing perspective freely.

6.1.1 Viewing Perspectives for Streaming VR Games

Watching others play games via live streaming platforms has become common, and many content creators aim to improve the entertainment factor for maximal retention. For instance, most streamers complement the game's view with webcam footage to convey the entire gaming experience. VR games still take only a small but growing share of the enormous streaming market. However, the three-dimensional nature of immersive experiences challenges the established content creation pipelines of streamers. Compared to non-VR games, the player's sensations include both a head-orientation-dependent stereoscopic view and realistic controller interactions. Conveying this impression on the 2D displays most spectators use is challenging for any streamer.

Instead of using the standard first-person perspective, many streamers opt for a mixed-reality view to emphasize the player's presence in the virtual world. Therefore, the player is blended into the surrounding environment with the help of a greenscreen and the proper software [87]. This approach displays the player's full-body movements and interactions in the context of the VR scenario and improves the understanding of the events in the virtual world. Despite these advantages, we also see arguments for using the traditional first-person view. Compared to the mixed-reality approach, this perspective matches the player's view and takes the audience much closer to the action, conveying a similar experience to playing the game oneself.

Since both techniques are widely used in the streaming community, and each has individual benefits, we assume there is no universally favorable approach. Instead, the choice likely depends on the particular situation, such as the played game and type of audience. Consequently, we see an urgent need to expand our knowledge of the spectators' preferences and the impacts of the different perspectives on the viewing experience. We already know that high immersion is vital for a good VR experience, but its importance for the audience compared to other factors such as proper contextual understanding and player focus remains unclear.

With our publication [P8], we contribute these relevant insights into the spectators' preferences. Therefore, we conducted an online survey with 217 participants to explore how the first-person perspective compares against the third-person mixed reality view. As we were interested in the suitability for various game genres, we included three different VR games in our study: Beat Saber [53], Superhot VR [152], and Stand Out: VR Battle Royale [119] (see Figure 6.1). We chose these three titles because of their different attributes regarding pace, focus, and locomotion. Whereas Beat Saber is a static rhythm game with one primary orientation, Superhot VR features mostly stationary fighting where enemies approach from all sides. In contrast to the other two games, Stand Out is a first-person shooter with virtual locomotion and intense action.

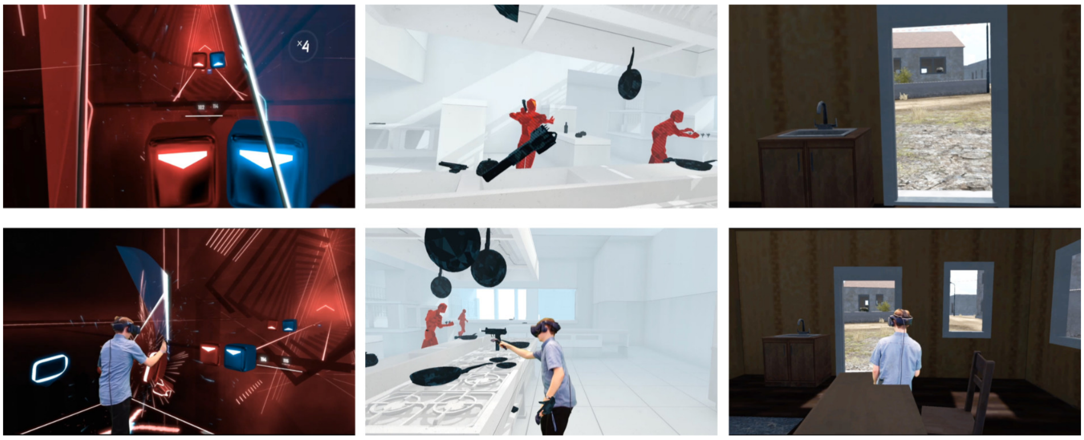

Figure 6.1: We compared two perspectives to stream VR content [P8]: a first-person perspective (top) and a third-person mixed reality view (bottom). Subjects watched gameplay from three games: Beat Saber, Superhot VR, and Stand Out: VR Battle Royale (left to right).

For each game, the subjects watched two videos - one for each perspective - before rating their experience in a questionnaire.

Our results reveal two key factors that come into play when deciding on the best viewing perspective: the game characteristics and the audience's expectations. Depending on how the game's actions and events are spread in the virtual environment, the choice of the most suitable perspective varies. Whereas the first-person view focuses primarily on the game, the mixed-reality perspective emphasizes the players and their actions in the virtual world. Games, in which most events evolve in close proximity, profit from the unique insights viewers gain from seeing the players' movements in the third-person perspective. Naturally, this benefit mainly applies to games with interesting and distinctive movements. In turn, the first-person perspective provides a better and more focused view of the relevant events if the main action is distributed over the virtual environment and not centered around the players.

Apart from the game's properties, the audience's expectations and motives also influence the perspective choice. If viewers are primarily interested in the game and less in the individual player, a first-person view provides a better impression of playing the game than the third-person perspective. In contrast, if spectators mainly aim to be entertained by a particular streamer, they might benefit more from the mixed-reality view, which focuses primarily on the player.

Even though this research focused on the spectator experience for streamed VR games, it also applies to other use cases featuring an audience. Specifically, our insights are highly relevant for any multiuser scenario combining VR and non-VR users. Especially in VR training applications, e.g., for surgical training, the correct perspective choice is essential to guarantee that the supervisor can monitor and evaluate the trainee's performance in VR adequately. Consequently, we see our publication as an essential first research step on how to incorporate non-VR audiences into immersive experiences.

6.1.2 Watching VR Content as a Local Observer

With the previous publication, we focused exclusively on streaming VR experiences online. This remote content must be in an accessible format, such as a single 2D video, to guarantee that spectators can watch the game regardless of their device. For this specific context, our research revealed a range of factors to consider when choosing the best viewing perspective. However, limiting the spectators' impression to a fixed viewing angle and single video output is not necessarily the best approach for a physically present audience.

In most cases, interested bystanders may watch the VR view only on an adjacent screen while seeing the players' movements in the real world. Consequently, spectators must follow both information streams concurrently and use their imagination to project the player into the virtual environment. The alternative approach of using a mixed-reality view automates this projection by blending the players at the correct position in the virtual world [87]. However, technical constraints usually limit such setups to a fixed viewing angle. Hence, spectators will miss any event that happens outside of this view frustum. Additionally, this approach is often used only for producing game trailers and advertising due to the high cost and complexity.

In summary, both concepts that worked well for streamed content are not ideal solutions for a physical audience. The first-person view introduces an additional mental overhead of following two sources of information simultaneously and does not convey the feeling of being present in the virtual environment. In turn, the highly complex mixed-reality setup is not suited for spontaneous viewing and might miss on important events that happen behind the spectator camera. Consequently, we see great potential for further research in this field to dispel these barriers impeding an easy and pleasant viewing experience for interested bystanders.

With our second publication [P10], we contribute to this research topic by designing a novel display that allows external viewers to watch the player's actions in VR. Our concept's core is a device built from a one-sided mirror and a monitor attached to its back (see Figure 6.2). In the mirror, spectators see the player merged into the virtual environment, similar to using a greenscreen. Therefore, we use Vive Trackers [66] to capture the mirror's and the spectator's position. We use this data together with the HMD position to calculate an immersive and view-dependent image. When looking in the mirror, the spectators see the virtual world according to their position in the

Figure 6.2: Our novel mixed-reality display [P10] allows local bystanders to watch the player's actions in VR by blending the player's real reflection with the virtual surroundings. Observers can change their viewing angle by walking through the play space.

physical play space. Additionally, we have developed a silhouetting algorithm to render a dark overlay at the position of the player's reflection. In this darkened area, viewers see the physical reflection of the one-sided mirror, that is, the real player.

In contrast to the previous mixed-reality approach, our concept allows spectators to control the view frustum intuitively by walking through the tracking space. Apart from greatly increasing the viewers' autonomy, this approach replaces the static display experience with a window into the virtual world. Observers may try different perspectives and alter their view to avoid missing important events. Additionally, our technique does not require the additional capturing overhead that is needed with greenscreen settings for merging the VR footage with the information from an external camera.

Apart from developing this novel viewing concept, we also conducted an exploratory study to gather first impressions and feedback. Therefore, participants watched a live VR gaming session through our mirror devices and could freely move around the room to adjust their view frustum. Afterward, we administered various questionnaires and used a semistructured interview to collect further remarks. Our results revealed an overall positive appreciation of our concept. In particular, the mirror's main strengths lie within the superior comprehensibility of the player's actions and the additional freedom of autonomous exploration.

These two primary benefits are vital in making VR content better accessible for external non-VR viewers. Also, our approach lowers the traditional blocking barrier between audience and players and evokes a feeling of being present in a shared virtual world. The findings may pave the way toward other novel experiences for including the traditionally passive spectator in an engaging mixed-reality action. Therefore, we see our contribution as a decisive step toward further research on collocated asymmetric VR experiences.

6.2 VR Exergame Design

In the second half of this chapter, we look at one of the most popular use cases of VR devices: gamified physical training. Most people know that regular exercise is vital for our physical well-being and associated with various benefits, such as delaying aging processes [44] and improving cognitive functions [107]. However, this theoretical knowledge alone usually does not lead to a more active and healthy lifestyle. Instead, strong and lasting incentives are needed to motivate people to exercise on a regular basis [26]. One concept that has been found particularly useful in providing this motivation is VR exergames. A viral example is Beat Saber [53], which we already covered in the previous section. These fitness games allow users to combine enjoyable gaming activities with healthy physical exercises while staying in the comfort of their homes.

Despite these advantages, such exergames can only complement but not replace traditional exercise routines. One important reason resides in the type of movements players perform in VR. Most currently available exergames, such as BoxVR [50], base their gameplay on hand motions alone. Consequently, the training effect is limited to cardiovascular improvements and upper body fitness instead of training the entire body. We see great vacant potential in this design decision. In particular, as most people spend most of their day sitting, lower body exercises are indispensable to prevent undertraining of the lower limbs.

However, incorporating such full-body movements into an immersive experience is highly challenging. In contrast to stationary hand-based exercises, lower-body motions typically require players to move considerably in the physical play space, which bears the risk of dangerous collisions. Also, before users may perform explosive movements while wearing a heavy HMD, other potential impediments that can cause injuries or deteriorate the user experience must be identified and dispelled first. In particular, we see the primary challenges in headset stability and tracking precision during the fast-paced exercises.

Apart from these safety concerns, designing effective exergames that target the entire body also requires considering proper training routines and fitting feedback. Full-body movements are likely more complex than the simple arm swings in Beat Saber [53] and bear a greater risk of misexecution. Also, as this topic is largely unexplored, there

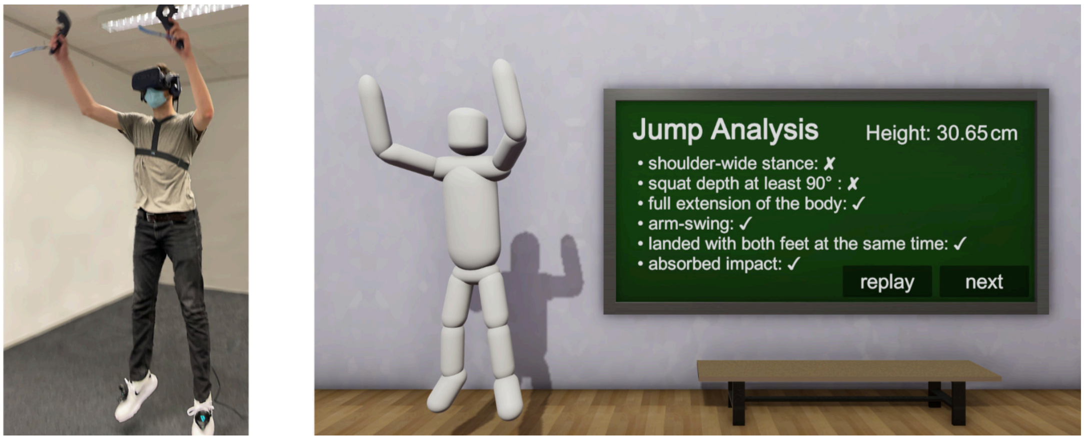

Figure 6.3: Our first prototype confirmed that users could safely perform maximal vertical jumps in VR [P5]. After each jump, users see a replay and an analysis of jump-related criteria.

are no prior experiences or existing design guidelines. Consequently, we see the high importance of including domain experts in the game design pipeline to ensure safe and efficient training.

In our work [P1, P5], we introduce this highly complex topic and explore the potential of full-body VR exergames. Considering the vast design space for such experiences, we focus on a concrete example: the vertical jump. Being a basic skill that we learned at a very young age, jumps are used for various purposes and in many situations. Apart from jumping-intense sports, like basketball [35] or volleyball [118], jumping is also widely used to assess general fitness [58], neuromuscular coordination [94], and muscle composition [17]. Additionally, we consider the vertical jump to be a perfect example movement for our exergame research. Despite being a highly explosive motion that challenges tracking precision and headset stability, jumps do not require an extensive tracking area. Also, jumping can be improved through various training modalities and combined with other movements to achieve a diversified gaming experience.

Since most jumping-related sports research targets professional athletes and little prior work covered jumping in virtual environments, we structured our research into multiple phases. In our first publication [P5], we laid the foundations for our exergame design. First, we reviewed the related work on VR-based training, jumping-related biomechanical basics, and training modalities for the vertical jump. We used these insights to discuss possible features of VR-based jump training:

- measuring the user's own training progress
- fostering intrinsic learning by visualizing the user's own jumps
- providing individualized feedback, analysis, and training recommendations
- increasing the motivation through gamified exercises

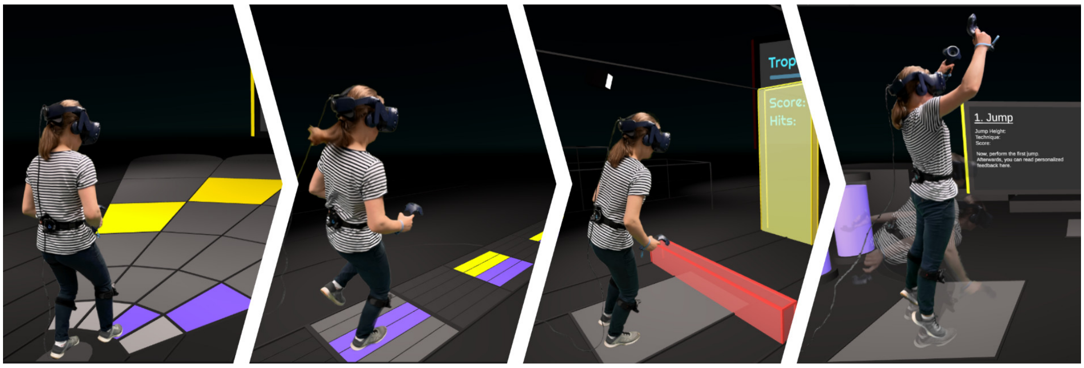

Figure 6.4: Our VR exergame for vertical jump training [P1]. In the first three levels, players perform movements to the rhythm of a song: tapping on colored tiles, hopping on the spot, and dodging obstacles. The last level gives personalized feedback on five maximal jumps.

Next, we used a participatory design phase to develop an early prototype featuring a subset of the discussed features (see Figure 6.3). Therefore, we recorded the users' movements by attaching Vive Trackers [66] to their feet and provided personalized feedback after each jump. With the help of this application, we demonstrated the general feasibility of using VR for engaging jump training. Furthermore, we confirmed that the headset stability is satisfactory. Even though jumps frequently cause tracking quality to deteriorate noticeably, this limitation does not preclude a future adoption in training applications for amateurs.

In our second publication [P1], we designed and evaluated a VR exergame that features jumping-related movements and aims for physical exertion, motivation, and constructive feedback. Therefore, we started by conducting a semistructured interview with experts from various domains, such as sports research or physiotherapy. After interviewing nine experts, we transcribed and translated the recordings and used a thematic analysis approach [21, 22] to extract valuable insights. This process yielded four main themes, covering the benefits of jump training, the correct execution of a countermovement jump, guidelines for providing constructive feedback, and possible challenges for VR exergames.

Based on the experts' recommendations, we developed a VR exergame to train the vertical jump (see Figure 6.4). Our primary focus was on motivating players to exercise in a fun way while avoiding any injuries or frustration due to an improper difficulty. As many experts proposed raising the difficulty gradually, we developed four sequential levels that start with simple steps before switching from hops to larger leaps and, finally, maximal vertical jumps. In the first three levels, players perform the correct movements — taps, hops, jumps — to the rhythm of a song. The difficulty changes dynamically based on the player's current performance. These levels are mainly intended as a warmup and train a variety of prerequisites for the later vertical jump, namely lower body coordination, stability, muscle strength, endurance, and neuromuscular control.

Finally, the last level focuses on the maximal vertical jump and a proper jumping technique. In contrast to the first levels, this part is not time-controlled and features only five jump executions to enable players to concentrate on their improvements rather than exertion. Therefore, the game continuously scans the player's movements until it detects a jump. Afterward, the collected data is analyzed concerning four criteria of a safe and efficient jump that the domain experts proposed:

- jump and land with both feet simultaneously
- land softly and absorb the impact with the entire body
- especially while landing, keep the knees in one line between feet and hips and do not cave them inward
- swing arms synchronously in a forward-upward arc until about chest height

The players receive individual feedback after every jump, depending on their performance in these categories. Additionally, they can study their own movements that are displayed as a looping replay in front of them. These game elements combine extrinsic instructions with intrinsic feedback for optimal training results. Finally, the players see their progress in jump height and technique score across the five jumps on a leaderboard.

In the last part of our work, we evaluated how users perceive the training experience of our exergame. Therefore, we conducted an exploratory study to explore the perceptual, motivational, and physical effects. Our results revealed that the participants enjoyed engaging in a leg-based exergame. Additionally, they appreciated the physical challenge and felt more energetic after the game. Lastly, we detected a significant increase in cybersickness. However, we attribute this finding entirely to the participants' sweating, which is measured by the chosen questionnaire but is an expected effect when exercising. We concluded our publication by discussing our development process and deriving a set of design guidelines that help researchers and practitioners expand on our work.

To summarize, our research explored how VR games can motivate players to increase their physical activities and work toward a healthier lifestyle. Exercises in VR are not limited to the arms alone; instead, incorporating full-body movements offers a great potential for future games. As our study demonstrated, even explosive jumps are possible while ensuring the safety and satisfaction of the users. On the contrary, we deem such experiences to be more effective than many available games, as they involve the entire body and thereby prevent undertraining certain muscle structures. However, technical limitations, such as tracking imprecisions, remain a significant challenge for developers. Finally, we strongly emphasize the value of our expert-knowledge-driven research approach. We are confident that by including domain experts in the game design pipeline from the very beginning, developers will ultimately achieve safer and more efficient training experiences.

6.3 Recap on Applications

In this chapter, we covered two application-centered topics. First, we investigated how non-VR spectators can better understand the player's experiences in the virtual world. Therefore, we compared two viewing perspectives for streamed content and envisioned a novel prototype for the local audience. In the second part, we explored the potential of exercising in VR by developing a jump-training exergame based on recommendations from domain experts. In contrast to the previous chapters, these contributions are not intended to improve or develop interaction concepts for immersive experiences in general. Instead, we focused on two requirements that determine how VR will evolve in the new future.

On the one hand, we need to make VR more accessible and remove the initial hurdles to prevent people from testing it. On the other hand, we should explore new fields where VR can help people by simplifying tasks or enabling novel approaches. We deem this last part especially vital for the future success of VR. For instance, we consider our particular use case - assisting players in establishing a healthier lifestyle, even though gyms and sports clubs might not be available - as such a meaningful application area where the unique benefits of VR setups can improve the status quo.

7 Conclusion

In this dissertation, we covered four aspects of virtual experiences and VR research: locomotion, interaction, perspectives, and applications. First, we covered four novel locomotion approaches for different use cases. Our GulliVR and Outstanding concepts employ virtual body scaling to explore large open VR environments easily by natural walking. As these techniques are less suited for more narrow surroundings, we designed an alternative concept that uses a space-bending tunnel to prevent cybersickness when scaling only the user's forward movement. Our fourth technique, Tug & Swing, combines two gesture-based locomotion approaches to achieve fluent and precise navigation for stationary VR setups that are too small for natural walking.

After exploring how users can travel effortlessly through virtual environments, we widened our view and more thoroughly covered VR interaction in general. Before dealing with novel interaction concepts, we first confirmed that users behave as intended and do not break with the virtual world's rules just because they can. With this knowledge, we explored different design approaches for a novel input modality to improve sneaking in VR games. One of the main takeaways is the finding that gait-related interactions do not require the same tracking fidelity as controller input. Lastly, we investigated the peculiarities of VR interface design by formalizing the design choices for inventories in a structural taxonomy.

In the third part, we switched our research focus from the users' interactions with the virtual world to their assumed role in the scenario. In particular, we extended the traditional approach of embodying a single human avatar in two new research directions. First, we transferred the illusion of virtual body ownership to animal avatars and explored how to integrate this sensation into engaging experiences. In the second part, we challenged the conventional way of experiencing stories in VR from a single point of view. Therefore, we investigated how multiprotagonist narratives can be employed in VR storytelling by using transition concepts that allow users to switch dynamically between different playable characters.

In the last chapter, we covered the general use of VR applications in everyday life. In our first project, we focused on the typical problem of most VR systems: external spectators cannot easily watch the user's experience without wearing headsets themselves. To reduce these barriers between VR players and their audience, we compared the suitability of different viewing perspectives for various streamed VR games. Also, we proposed a novel prototype that permits local bystanders to watch the VR content in an immersive mixed-reality view from their preferred angle. In the second project, we explored how VR games can be used to train full-body movements, such as the vertical jump. Therefore, we designed and evaluated an exergame based on recommendations from sports experts.

Overall, we covered a great variety of different research topics. However, the value of a particular publication always depends on its value to the community, its practical applicability, and the potential for follow-up work. Hence, we finish this synopsis with a critical view on our contributions and their potential future impact.

7.1 A Critical Look Ahead

In total, this dissertation comprises 17 publications. They differ greatly in their particular research focus, use different methodologies, and are published at various venues. Hence, assessing and comparing their impact on VR and HCI research is challenging. Of course, we could consult performance metrics such as the citation count. However, these numbers mainly depend on the publication date and less on the actual impact. Additionally, much of our research is still in the publication pipeline. Therefore, it is no surprise that our most cited publications are the ones on virtual body scaling, i.e., GulliVR and Outstanding, and the ones on animal body ownership. These papers were simply published the earliest. In sum, we see little value in consulting the crystal ball to guess the future impact of a specific paper. Instead, we want to discuss our ideas about how future research will revolve around our central question: *How can we design a virtual experience that feels natural and fluent?* Therefore, we subdivide the discussion into the four initial questions that guided our research in each of the chapters.

How do we move through extensive virtual environments?
Finding proper answers to this question is a fundamental prerequisite for realizing sophisticated VR experiences. Hence, we discussed this topic extensively and presented a range of up-and-coming concepts, such as the virtual body scaling or the space-bending tunnel that reduces the visual flow. In each of our publications, we raised open issues and possible improvements to our presented techniques that are worth investigating in future research. For example, even though our tunnel concept proved very effective in our study, we do not yet know the gain factor's upper bound where the technique still remains usable. Similarly, extending the concept to curved paths and dynamic targets allows for broader applicability. Whereas this follow-up work is vital, we see the main priority of future locomotion research to be consolidating the

widespread and ever-growing field of published locomotion techniques. Consequently, efforts such as the LocomotionVault are critical to streamline the research efforts and provide researchers and practitioners with a comprehensible overview of the current research state.

How can we interact with our virtual surroundings?
Our primary contribution to this question is our gait-related input modality. We see great potential in such novel interaction concepts that enrich the virtual experience. Of course, our particular technique offers various future research directions. First, stealth games could greatly profit from complementing our sneaking implementation with additional channels, such as synchronized audio feedback. Also, our precise footstep tracking might be also interesting for other application domains, e.g., dance training. Apart from this follow-up work on our presented input modality, we also see the ongoing importance of opening the mind and envisioning similar novel interactions that extend our experience in the virtual world beyond our usual expectations.

Our second focus in this field is on the design of suitable user interfaces for VR. Our inventory taxonomy laid the foundation for follow-up research in this direction. In particular, we emphasize the importance of evaluating the interplay between the initial requirements and the various design choices to achieve an easily usable interface. In this context, inventories are particularly complicated to design as they are deeply connected to the virtual world while remaining a detached menu. In addition to further research on this topic, we propose to rethink how users interact with the environment's items and how these interactions are designed to feel natural and believable.

Whom do we become when entering a virtual world?
With our pioneering work in the area, we introduced the concept of virtual body ownership to two entirely new research directions. Our confirmation that IVBO applies to animal avatars opens a vast range of future research directions. We have already explored first integrations in engaging experiences and demonstrated the potential for VR games. Additionally, we assume that our detected effect is of value for other domains. For instance, embodying an animal in VR could increase the players' empathy, which would be of great use to increase the overall awareness for conservation methods or to fight animal-related fears. In our second project, we extended body ownership to multiple playable characters. Switching dynamically between different avatars is essential for narrating complex multiprotagonist plots in VR. Nowadays, when more and more people encapsulate themselves in a bubble, and block opposing views, such applications have the potential to foster the players' perspective-taking and widen their point of view. Hence, we see an urgent need for follow-up research that builds on our findings to improve the technical foundation for such multiprotagonist narratives.

How can we use VR in everyday life?
Despite the growing spread of consumer headsets, most people do not own a VR headset. Consequently, we first answered this question by improving the spectator experience for remote and present non-VR observers. Even though there are still open questions to be answered in order to achieve an optimal viewing experience, our main priority is our second project. In our most recent publications, we have extended the traditional VR exergame experience to full-body movements. By involving domain experts in our game design phase, we ensured that our jump-training application builds on insight-driven knowledge and provides a safe and pleasant user experience. With this work, we demonstrate the potential of VR systems for individual unsupervised exercises that are integrated into an engaging game. For the next steps, we suggest expanding on this fundamental work by improving the automated feedback, evaluating the long-term effects compared to supervised training, and extending the lessons learned to other promising domains.

Publications and Submissions

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Declaration

I hereby declare that I have completed this work solely and only with the help of the references I mentioned.

Duisburg, Germany, October 19, 2022

Sebastian Cmentowski

Locomotion

Virtual Body Scaling	**GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing** *(CHI PLAY '18)* **Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games** *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put...": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing

Andrey Krekhov, Sebastian Cmentowski, Katharina Emmerich, Maic Masuch, and Jens Krüger. 2018. GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY'18)*. ACM, Melbourne, VIC, Australia, 243-256. DOI: 10.1145/3242671.3242704.

Outstanding: A Perspective-Switching Technique for Covering Large Distances in VR Games

Sebastian Cmentowski, Andrey Krekhov, and Jens Krüger. 2019. Outstanding: A Perspective-Switching Technique for Covering Large Distances in VR Games. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (CHI EA '19)*. ACM, Glasgow, Scotland Uk, 1-6. DOI: 10.1145/3290607.3312783.

Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games

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GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing

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Figure 1. GulliVR allows players to become giants on demand and to traverse larger distances in room-scale VR setups within a few steps. The modeled eye distance is enlarged proportionally to the virtual body size, which ensures the absence of cybersickness.

ABSTRACT
Virtual reality games are often centered around our feeling of "being there". That presence can be significantly enhanced by supporting physical walking. Although modern virtual reality systems enable room-scale motions, the size of our living rooms is not enough to explore vast virtual environments. Developers bypass that limitation by adding virtual navigation such as teleportation. Although such techniques are intended (or designed) to extend but not replace natural walking, what we often observe are nonmoving players beaming to a location that is one real step ahead. Our navigation metaphor emphasizes physical walking by promoting players into giants on demand to cover large distances. In contrast to flying, our technique proportionally increases the modeled eye distance, preventing cybersickness and creating the feeling of being in a miniature world. Our evaluations underpin a significantly increased presence and walking distance compared to the teleportation approach. Finally, we derive a set of game design implications related to the integration of our technique.

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CCS Concepts
•Human-centered computing → Virtual reality; •Software and its engineering → Interactive games; *Virtual worlds software;*

Author Keywords
Virtual reality games; navigation; physical walking; presence; virtual body size; miniature world.

INTRODUCTION
The number of players who discover virtual reality (VR) games for themselves is steadily increasing. Players enjoy the experienced presence in varying virtual worlds, and game developers attempt to design player interaction to be as natural as possible to further enhance the players' feeling of being there.

In particular, room-scale systems offer the most natural kind of navigation for games–physical walking. Although researchers have emphasized the superiority of that "technique" over approaches such as walking in place or flying [67] regarding presence, the size of our living rooms imposes a significant limitation that needs to be bypassed. One of the most prominent remedies promoted by VR systems is the teleport method, which has been developed as addition to common walking to overcome the room size restriction. However, in reality, we observe that players hardly move at all. Instead, they teleport to a location that may be only one step ahead.

Our research attempts to increase the amount of player movement and the experienced presence by introducing a novel natural walking navigation technique. Inspired by *Gulliver's Travels* [64], the idea behind our *GulliVR* approach is to enlarge the virtual body of the player on demand to allow travel over large distances within a few steps, as depicted in Figure 1. In the giant mode, we proportionally increase the modeled eye distance to keep the physical movement and the perceived visual feedback in sync, which prevents cybersickness and creates the impression of walking through a miniature world.

Scaling for navigation purposes is not novel in VR and is often employed in world-in-miniature [62] techniques that rely on a demagnified version of the world. Scaling the user is known from multi-scale VR applications [1] and is closely related to our method. The key difference and our first contribution is that we explicitly modify the depth perception by adjusting the modeled eye separation on the fly to match the player size and, thus, to prevent cybersickness. As a byproduct, the altered depth perception in the enlarged mode leads to an impression of navigating through a toy world.

Our second contribution is the application of navigation-related player rescaling to the domain of VR games. We demonstrate a possible embedding of our technique in a 3D adventure and compare our method to the state of the art teleportation approach. The study reveals a significant increase in presence when using GulliVR, which is a valuable reason for game developers to consider our method as a game mechanic. GulliVR is not a universal remedy for the VR navigation problem, but rather an alternative locomotion technique with its unique strengths and weaknesses. Therefore, our paper also exposes several game design implications that are meant to help developers to decide whether and how the method should be considered for a particular purpose.

RELATED WORK

Our work belongs to gaming-oriented VR locomotion research. We briefly introduce basic concepts of playing games in VR before discussing in depth the fundamental research on VR locomotion. As GulliVR is centered around the variation of pupillary distance and size perception phenomena, we also provide background related to these topics to explain the mechanisms behind our method.

Player Experience in Virtual Reality

Player experience is one of the most utilized and well-known concepts in our community and consists of multiple components, such as competence, challenge, immersion, and flow. Consequently, various established methods exist that allow measurement of the player experience, such as the evaluation approaches presented by Bernhaupt [2]. These approaches were further formalized by IJsselsteijn et al. [22, 23] and sublimed in the Game Experience Questionnaire (GEQ) [24]. Regarding the overall feelings and experiences of players, Poels et al. [46] summarized a game experience categorization based on a focus group study.

When addressing player experience in a virtual environment, immersion [7] often plays a leading role. The term *immersion* is mainly used to describe the technical quality of a VR setup [5, 56]. If we want to describe how immersive tools impact our perception, the term *presence* is usually chosen by researchers. For an in-depth description and formalization of immersion and presence, we point to the work by Slater et al. [59, 57]. The former paper [59] also illustrates how locomotion in particular impacts presence. Further definitions and measurement techniques related to presence, also referred to as the feeling of being there [20], can be found, e.g., in the work of Lombard et al. [40] and IJsselsteijn et al. [25].

Navigating in VR comes with the well-known risk of *cybersickness* [37]. Before focusing on that phenomenon, we mention two similar issues: motion sickness [42] and simulator sickness [33]. All three types are similar in their symptoms such as headache, eye strain, sweating, nausea, and vomiting. However, the cause usually differs. Motion sickness happens when our inner ear senses a movement that does not correspond to our visually perceived movement [50]. Note that motion sickness is sometimes used in VR context [45, 21]. Simulator sickness usually happens when a simulator, such as used for pilot training, does not exactly reproduce the visual movement [31]. That term is also commonly used in VR context, and researchers often rely on the Simulator Sickness Questionnaire (SSQ) [30] to evaluate a VR experience. The work by Stanney et al. [60] points out that these sicknesses are not the same and and are characterized by different predominant symptoms. Regarding the different reasons for cybersickness, we point the readers to the discussion by LaViola Jr [37]. Apart from the obvious technological issues such as flickering and lags, the author also provides a summary of the most prominent theories about cybersickness: sensory conflict theory (most accepted), poison theory, and postural instability theory. Applying the sensory conflict theory means that moving in VR should trigger an appropriate visual response, and vice versa, if we want to obviate cybersickness.

One possible approach to reduce cybersickness is a reduction of the field of view, as recently proposed by Fernandes et al. [16]. A broader discussion about the influence of the field of view on the VR experience can be found in the work of Lin et al. [39]. In the area of digital games, von Mammen et al. [70] conducted experiments by deliberately inducing cybersickness in VR game participants and determined that such games could still be enjoyable. Iskenderova et al. [28] went a step further by by providing the subjects with alcohol to see how it would influence the symptoms of cybersickness. Surprisingly, these symptoms were significantly reduced at a moderate blood alcohol level around 0.07%.

Locomotion

Designing navigation in VR games is a challenging task [19]. Most of the non-VR navigation techniques rely on joysticks and keyboards and induce static player poses, which reduces presence and leads to cybersickness due to sensory conflicts. In contrast, natural walking [53] or even just walking in place [59, 66] can significantly increase presence. Bhandari et al. [4] combined both walking approaches in their *Legomotion* algorithm and reported a higher presence compared to controller input. Another comparison was presented by Usoh et al. [67]: according to the authors, walking outperforms walking in place, and both are superior to flying regarding presence. That finding was another reason for us to establish the walking metaphor as a giant rather than flying as a bird. Natural walking is also more efficient compared to virtual travel when the navigation task resembles real-world behavior [63]. Furthermore, Ruddle et al. [54] demonstrated that walking positively influences the cognitive map in large environments.

The current state of the art regarding locomotion in VR games was recently summarized by Habgood et al. [19]. One conclusion drawn by the authors is "that short, fast movements in VR (with no acceleration or deceleration) don't appear to induce significant feelings of motion sickness for most users". Our prestudies confirm that finding, as the transformation into the giant mode was perceived most comfortable when carried out very quickly or instantly. An additional backup regarding fast movements can be found in the work of Medeiros et al. [41] and the guidelines by Yao et al. [75]. The same positive effect holds for the arc-based teleportation technique that is promoted and encouraged by the majority of established VR systems such as the HTC Vive [10].

The major issue of natural walking is the limited space, as players can take only a few steps in each direction. Hence, researchers are constantly attempting to overcome that obstacle by introducing novel navigation metaphors that go beyond the previously mentioned teleportation technique. For example, Interrante et al. [27] proposed *Seven League Boots*. The technique deduces the intended travel direction and augments the corresponding component while leaving other directions unscaled, allowing the user to travel forward at increased speed. Steinicke et al. [61] focused on geospatial environments as an application domain for VR where the virtual space clearly exceeds the tracked area. The authors suggested several hybrid approaches such as the rocket-belt metaphor as an alternative flying approach and visual bookmarks that allow quick jumps to previously marked locations of interest.

Certain locomotion techniques have not found their way into VR games due to their specific requirements. One example is the manifestation of the virtual treadmill concepts [58] in physical treadmills [13, 26]. Another important research direction is redirected walking [49, 48]. Such approaches imperceptibly rotate the virtual environment and force users to slightly change their walking direction. Users think that they are moving straight forward, whereas in reality, they are walking in a large circle. Due to the required space, redirected walking is rarely used for living room sized VR setups, and requires further adaptations [18, 15, 36, 6] to overcome that limitation.

Size and Distance in VR

GulliVR changes the size ratio between the virtual body and the virtual world. Hence, in the broader sense, our approach can be classified as a multiscale virtual environment (MSVE) navigation. In that context, the technique that most resembles GulliVR is *GiAnt* by Argelaguet et al. [1], but with the focus on automated speed and scale factor adjustments to account for negative effects such as diplopia [35]. Similar to our findings, the authors emphasize the advantages of providing a navigation speed that is perceived to be constant by users.

Other experiments on MSVE navigation techniques centered around the exploration of the human body were carried out by Kopper et al. [34], who confirmed that automatic scaling outperforms user-defined manual scaling. We incorporated these results in our experiment by predefining the virtual body size based on current game objectives. In contrast to the previously mentioned full-body scaling approaches, the Go-Go technique [47] changes only the size and reach of the virtual arm to allow the direct manipulation of distant objects.

LaViola Jr et al. [38] explored hands-free navigation possibilities in MSVE. Their step world-in-miniature (WIM [62]) widget, being a walkable mini-map, resembles our navigation as a giant over the miniature world. Similarly, Valkov et al. [68] introduced a combination of multitouch hand gestures and foot gestures to explore a WIM. To increase navigation precision, the preliminary work by Elvezio et al. [14] proposes to control the posture of our avatar after WIM-triggered travel by post-teleport previews. As suggested by Bruder et al. [6], such previews can also be used as virtual portals where users have to pass through to reach the displayed destination. The portal concept works especially well when such "doors" can be naturally integrated into the virtual scenario.

One issue of traditional WIM approaches is the lack of adaptation to differently scaled virtual worlds. To overcome that limitation, Wingrave et al. [73] proposed a scaled scrolling world-in-miniature (SSWIM). SSWIM allows users to zoom and scroll the miniature representation of the world, which simplifies navigation and interaction in cases when the world is very large or small.

An important question for game design using the GulliVR technique is whether and how such scale adjustments influence our perception and interaction in VR. In general, researchers agree that we usually underestimate distance in VR [17, 52, 11]. Although object size familiarity plays an important role for distance experiment [43, 44], the sense of our own body is a major factor regarding our judgments on objects' size and distance [32]. The body effect was also extensively studied by van der Hoort et al. [69], who concluded that a user in a large virtual body perceives the objects smaller and nearer. The effect perfectly aligns with our experiments: our subjects, as giants, reported seeing the environment as a miniature toy world. Although we do not display any body parts in our testbed game, the research by Jun et al. [29] might be an interesting starting point regarding the players' mental ability to step over virtual obstacles in a game, because the authors found that displaying large feet would allow the user to step over larger gaps.

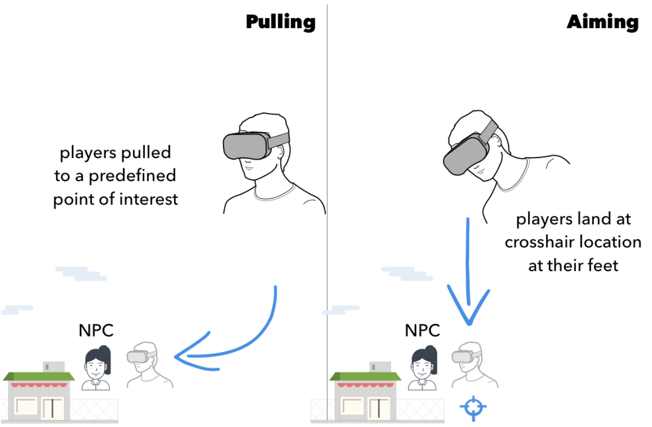

Figure 2. *Pulling* (left) and *aiming* (right) are two possibilities that allow precise transitions from GM to NM. Pulling adds a horizontal translation toward the nearby point of interest, whereas aiming displays a crosshair next to players' feet to indicate the destination location.

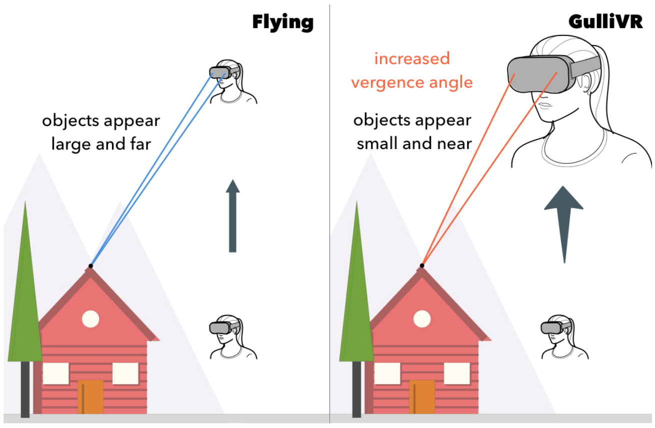

Figure 3. Significantly increasing the modeled eye distance results in a larger vergence angle, altering the size/distance perception of objects and evoking the feeling of being a giant. Physical movement speed is perfectly aligned with the visual feedback, which obviates cybersickness.

A major difference between flying navigation and GulliVR is the increased interpupillary distance (IPD) of the latter as a result of enlarging the whole virtual body. Although tiny variations of IPD have been shown to have no measurable impact on size judgments [3] and can even be applied unnoticed [71], setting the modeled eye separation to a significantly different value compared to the physical eye separation results in so-called *false eye separation* [9]. The resulting perceived image causes an altered size perception compared to real objects [72], leading to our miniature world perspective. Similar findings were also reported by Renner et al. [51], confirming that increasing the stereo base (i.e., the modeled eye distance) makes objects appear nearer and smaller.

GULLIVR NAVIGATION

The main idea behind GulliVR is to enlarge the virtual body of the player on demand. This *giant mode (GM)* allows the player to travel large distances in a room-scale environment using natural walking. Once the player reaches his or her destination, the virtual body size is reset to *normal mode (NM)*. Naturally, we can obtain the same results by shrinking the size of the world instead of enlarging the player. However, we would not recommend that approach in practice for performance reasons. For instance, having a fully resizable environment usually interferes with baked lighting.

Players need to control their transition from GM to NM, because "landing" somewhere offside is frustrating. We outline two approaches: active *aiming* and passive *pulling*, as depicted in Figure 2. Aiming can be realized by displaying crosshairs when the player looks down. Pulling is what we utilized for our testbed game. In that case, certain points of interest can be enhanced with bounding boxes. If the player initiates the transition to NM inside such a box, the virtual body is pulled toward the predefined interesting position, e.g., in front of an NPC. Triggering a transition outside the bounding box can be either prohibited or behave just like active aiming, with or without crosshairs. We assume that active aiming is more suited for games with free exploration modes, whereas pulling is useful for strictly scripted narrative flows.

At this point, we strongly emphasize the difference between enlarging the virtual body and flying, i.e., increasing the camera height and scaling its movement speed. In a nonstereo setup, both approaches would work identically. However, in a VR setup, players instantly note the difference. Enlarging the virtual body also means substantially increasing the modeled eye separation, as shown in Figure 3. Hence, players' size and distance perception of objects is altered [69, 51] and the world appears in miniature. This alteration has the important benefit that our physical walking speed is perfectly aligned with the visual feedback we receive. Flying, in contrast, usually promotes a cognitive mismatch. Hence, we assume that GulliVR does not induce cybersickness.

Cleary, GulliVR is not a universal remedy for all VR games, and we suppose that readers already have certain counterexamples, e.g., closed environments with ceilings, where the technique would perform poorly. Also note that GulliVR has notable degrees of freedom that developers should be aware of, e.g., GM size, object manipulation, and NPC interaction. We postpone a detailed discussion of the related design space, including possible limitations, until the section *"Design Implications"* to allow us to incorporate the results gathered from our experiments.

EVALUATION

We created a 3D adventure in VR to validate our technique and to explore its drawbacks. In our experiment, we compared a group of players relying on the common arc teleportation method to a group of subjects using GulliVR and measured aspects such as presence and physical walking distances. In addition to this game experiment, we asked the participants to perform several targeting tasks with GulliVR to see how precisely they could tell the system where to arrive after transitioning back to NM.

Hypotheses

The main assumption regarding GulliVR is that emphasizing natural walking should have a positive influence on the players' presence perception. Furthermore, we assume that

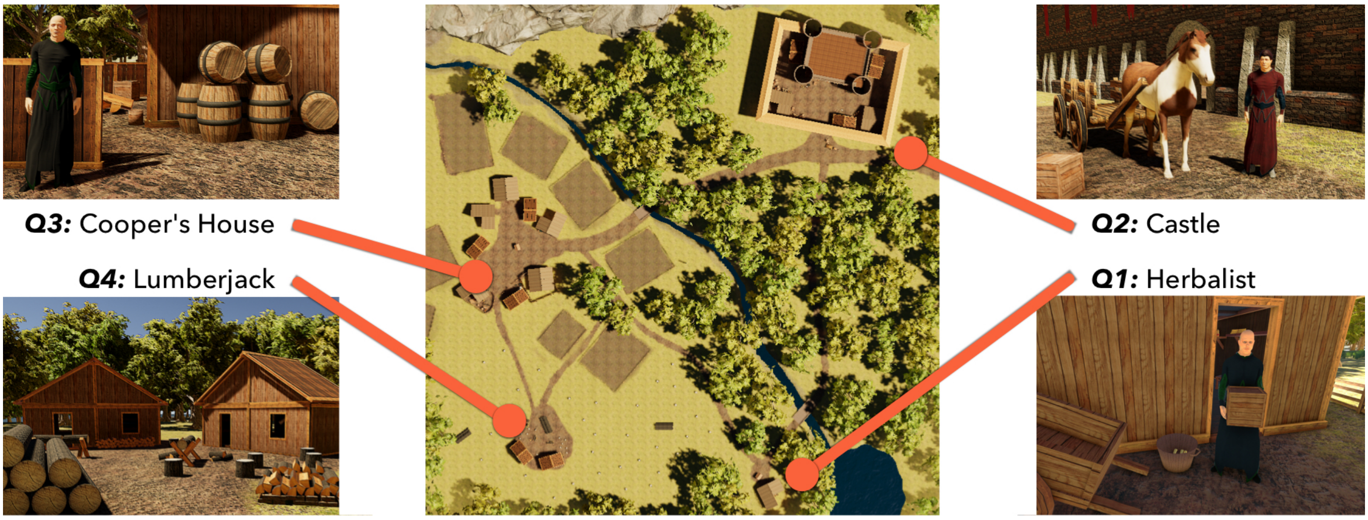

Figure 4. Overview of the virtual testbed game, including points of interest and related quests.

our manipulations with the modeled eye distance successfully prevent cybersickness, because there is no cognitive mismatch due to the alignment of visual feedback with physical movement. Finally, we hypothesize that players walk significantly more in GulliVR mode compared to the teleport technique. Although teleporting does not prohibit walking, our previous observations indicate that players stay rather still, even if the target is very close. To summarize, our three main hypotheses are:

- H1: GulliVR **significantly increases players' presence** compared to the teleport technique.
- H2: There is **no cybersickness** in the GulliVR mode.
- H3: In comparison to the teleport technique, **players walk significantly more** when using GulliVR.

Testbed Scenario

Our testbed adventure game is realized with the Unity 3D Engine [65] and takes place in a medieval, fictive world. The main character is an herbalist's apprentice in a rural area next to a famous castle. In our scenario, the player experiences one day in the life of the apprentice, solves simple quests, and explores the surrounding points of interest.

The world map is depicted in Figure 4. The player's journey begins in front of the lonely forest house of the herbalist. The herbalist asks the player to take the crate he is holding and to put it on a nearby cart (***Q1***). This first interaction allows the subjects to get familiar with object manipulation by using the trigger button of the controller.

Upon successful completion of the first task, the herbalist tells the player to pick up a healing scroll from the basket and to take it to the diseased lord of a nearby castle (***Q2***). The player also receives a detailed description to get to the castle. As a hint, the herbalist recommends the player make use of the navigation mode, i.e., teleport or GulliVR, for traversing larger distances by pressing the thumb button.

After a while, the player arrives at the castle and encounters a servant, already awaiting the scroll. Handing the scroll over finishes ***Q2***, and the servant asks the player to load supply crates (***Q3***) on a cart while he delivers the scroll to the lord.

Loading at least three crates triggers the servant to come back and tell the player to revisit the herbalist (***Q3***), who is in a nearby village by now. The herbalist waits in front of the cooper's house and requests the player's help one last time. The cooper needs some logs, and the player is asked to fetch them from the lumberjack (***Q4***). The quest is completed when the player delivers at least four logs. At this point, the scripted part of the game is completed. In an additional part of the game, the player can freely explore the world. A few changes are triggered. First, most of the game objects such as barrels become interactive. Second, a number of Easter eggs are added, e.g., the herbalist's house contains now a candle that, upon being picked up, shifts the game into night mode.

GulliVR Configuration

In GulliVR mode, the transformation between GM and NM takes 0.5 seconds. We chose that time based on a pretest ($N = 5$), because we had determined that any time slower than one second causes serious cybersickness, which is aligned with previous research [19]. We also preferred fast transformation over instant switching to prevent possible disorientation.

We chose the passive pulling approach for the transition from GM to NM. Quest-related areas, i.e., the castle, the cooper's house, and the lumberjack's house, are enhanced by invisible bounding boxes. Standing inside these areas and triggering the transition pulls the player toward the intended position, e.g., in front of the herbalist. This additional horizontal vector during the downward transition is imperceptible due to the very short transformation time. Going from GM to NM outside the quest-related bounding boxes shrinks the players, but does not pull them in any direction.

The scaling factor for the virtual body is automatically selected with respect to the current quest. Before the completion of ***Q3***, the GM is roughly 100*x* larger than NM, since the locations are further away. For ***Q4***, i.e., fetching logs, the destination is much closer, and we chose 30*x* as the scaling factor (cf. Figure 5).

Procedure and Applied Measures

We conducted a between-subject experiment with the navigation mode (cf. Figure 5), i.e., teleport and GulliVR, as the independent variable. The main reason for choosing a between-subject design was to minimize sequence effects from repeating quests and from possible cybersickness symptoms. On average, the study took 45 minutes and was conducted in our VR research lab equipped with an HTC Vive. After informing subjects about the study's procedure, we administered a questionnaire to assess age, gender, digital gaming behavior, and prior experiences with VR systems. Furthermore, as a control variable, we used the Immersive Tendencies Questionnaire (ITQ) [74] to assess how easily participants get immersed in activities like gaming and watching movies. The ITQ includes the four subscales *involvement*, *focus*, *games*, and *emotions*. We then introduced the subjects to the HTC Vive and explained the game controls: the trigger button is for picking and holding objects, and the thumb button activates the navigation mode.

In the teleport case, we explicitly explained how the teleportation works. In the GulliVR condition, we mentioned only that the thumb button triggers a navigation mechanism that is helpful for the traversal of larger distances. We intentionally neither embedded the technique in the story context nor provided any relational cues that could bias the subjects' impression of being a giant in order to gather reliable knowledge on how clueless players would perceive such a perspective.

After the briefing, subjects played the first part of the game (***Q1***-***Q4***). We logged all quest durations, interactions, and the physical distance traveled by the subjects. Upon completion of the final quest, an in-game message indicated a pause and advised the participants to remove the head-mounted display.

Subsequently, we administered questionnaires related to presence, player experience, and cybersickness. To assess feelings of presence, we relied on the Igroup Presence Questionnaire (IPQ) [55]. The IPQ contains the three subdimensions *spatial presence*, *involvement*, and *experienced realism*, as well as one single item to assess perceived general presence (*"In the computer generated world, I had a sense of 'being there' "*). All items are phrased as statements that participants have to rate on a 7-point Likert scale (coded 0 - 6).

As we are particularly interested in the influence of our navigation technique on feelings of presence, we additionally administered the Presence Questionnaire (PQ) (originally developed by Witmer and Singer [74] and revised by the UQO Cyberpsychology Lab [12]). The PQ includes the subdimensions *realism*, *possibility to act*, *quality of interface*, *possibility to examine*, and *self-evaluation of performance* (coded 0 - 6). By focusing more on the interactions with and navigation through the game environment, the PQ is a good complement of the IPQ to assess all aspects of presence.

Figure 5. Player's perspective when using the arc teleportation technique (left) and in GulliVR mode (right) with 30*x* virtual body scaling.

To measure further dimensions of the overall player experience, we applied the Game Experience Questionnaire (GEQ) [24], which consists of seven subscales: *positive affect*, *negative affect*, *immersion*, *flow*, *challenge*, *tension/annoyance*, and *competence*. All 33 items are presented in the form of statements to which participants rate their agreement on a 5-point Likert scale (coded 0 - 4). The Simulator Sickness Questionnaire (SSQ) [30] was administered to test whether one of our navigation techniques or the game in general causes any negative physical reactions in terms of cybersickness. It assesses symptoms of cybersickness on the three subscales *nausea*, *oculomotor*, and *disorientation* on a rating scale ranging from 0 (none) to 3 (severe). Finally, we asked some custom questions specifically addressing the navigation technique used for which participants had to rate their agreement on a 7-point Likert scale (see Table 3).

Upon the completion of the questionnaires, we asked the subjects to return into the virtual reality and freely explore the world. To trigger the players' desire to explore, we mentioned that a certain amount of Easter eggs had been added since their last VR visit. As in the first game round, we logged all interactions, traveled distances, and the overall exploration duration. The subjects were asked to give a signal when they felt that they played enough. Otherwise, we stopped the exploration mode after 20 minutes.

The third part of our experiment consisted of a targeting task and was the same for both condition groups, with the teleport group receiving a brief introduction into the GulliVR technique. We placed the participants into GM (100*x*) and showcased the four target circles as shown in Figure 6. We asked the subject to attempt to get in the middle of each circle and then switch to NM. After the transformation, the target was colored in accordance with the hit zone. Each target could be visited only twice, and immediate reattempts were not possible. After eight hits, an in-game message indicated the completion of the overall study.

RESULTS

Sample Description

In sum, 30 persons (15 female) participated in our study with a mean age of 27.6 ($SD = 11.18$). All participants reported playing digital games at least a few times a month and the majority of them (26) had also used VR gaming systems before, but they had little experience with such systems. Participants were randomly assigned to one of the two study conditions (GulliVR vs. teleportation navigation). Participants in the

Table 1. Mean scores, standard deviations, and independent samples t-test values of the iGroup Presence Questionnaire (IPQ) and the Presence Questionnaire (PQ).

	GulliVR ($N = 15$) M (SD)	Teleportation ($N = 15$) M (SD)	t (28)	Significance p	
IPQ (scale: 0 - 6)					
Spatial Presence	3.84 (0.73)	3.21 (0.93)	-2.05	.050	
Involvement	3.42 (0.82)	3.07 (1.11)	-0.98	.334	
Realism	2.50 (0.75)	2.17 (0.63)	-1.32	.199	
General	4.40 (1.12)	3.00 (1.51)	-2.88	.008	**
PQ (scale: 0 - 6)					
Realism	4.33 (0.84)	3.33 (0.63)	-3.69	.001	**
Possibility to Act	4.12 (0.94)	3.27 (0.79)	-2.67	.013	*
Interface Quality	5.20 (0.77)	5.13 (0.70)	-0.25	.806	
Possibility to Examine	4.78 (0.81)	3.98 (0.88)	-2.59	.015	*
Performance	4.70 (0.92)	4.67 (1.32)	-0.08	.937	
Total	4.53 (0.60)	3.85 (0.55)	-3.28	.003	**

*p <.05, ** p <.01

two groups did not differ significantly regarding their distribution of age, gender, and prior experience with VR games. Furthermore, there was no significant difference regarding the immersive tendencies of our subjects ($t = 1.47$, $p = .152$).

Testing the Hypotheses

We compared the results of our measures between the two study conditions. For each analysis, we tested the requirements for parametric calculations (homogeneity of variances and normal distribution of data) with Levene's and Kolmogorov-Smirnov tests. If the requirements were violated, Mann-Whitney U tests are reported instead of independent samples t-tests for testing significant differences between the groups.

Concerning H1, we compared the measures of presence between the two study conditions. Table 1 shows the scores of the IPQ and the results of the calculated independent samples t-tests. For all subdimensions, the GulliVR group scored higher than the group using teleportation. Only the difference regarding the general feeling of presence is significant according to the analysis (p = .008), although spatial presence is just on the edge of being significant as well (p = .050). Table 1 summarizes the mean scores of the PQ and the results of the t-tests comparing the two groups. Similar to the IPQ scores, the GulliVR group shows a clear tendency to experience higher presence, as mean values are higher for all dimensions. The analysis reveals that the differences in experienced realism, the possibilities to act and examine, and the total presence score are significant. In contrast, the quality of the VR interface and the self-evaluation of performance do not differ significantly.

As stated in H2, we wanted to assure that GulliVR does not negatively affect players in terms of cybersickness. Table 2 shows the weighted scale scores of the SSQ, which are all rather low. With respect to reference values reported by Kennedy et al. [30], our values indicate that participants had no significant problems with cybersickness in either condition. When comparing the SSQ values of both study groups, participants in the GulliVR condition tended to report fewer symptoms than participants using the teleportation navigation. However, according to Mann-Whitney U-tests, these differences are not significant (all $p > .067$).

Table 2. Mean scores and standard deviations of the Simulator Sickness Questionnaire (SSQ).

SSQ Dimension	GulliVR ($N = 15$) M (SD)	Teleport ($N = 15$) M (SD)
Nausea	3.82 (6.03)	14.63 (19.37)
Oculomotor	10.61 (10.25)	16.68 (18.83)
Disorientation	13.92 (20.38)	22.27 (26.72)
Total	10.47 (10.21)	19.95 (21.24)

In H3, we assumed that GulliVR encourages players to walk more, as they have to travel all distances by moving in the real world. Indeed, we observed that participants used the room more extensively in the GulliVR condition. This impression is confirmed by the analysis of the logged gameplay data. We measured the distance that players covered (in the real world) during the story part of the game and in the free exploration phase. As the playing duration was variable, we then calculated the mean score for walked meters per minute to have comparable values. On average, players using the GulliVR technique walked 14.75 meters per minute ($SD = 3.85$), whereas players in the teleportation group walked only 11.38 meters ($SD = 2.61$). A t-test indicates that this difference is highly significant ($t(28) = -2.81$, $p = .009$), supporting our hypothesis. The same effect was found for the free exploration phase: again, players in the GulliVR group walked more ($M = 10.92$ m/min, $SD = 3.06$) than players in the teleportation group ($M = 7.30$ m/min, $SD = 2.22$); $t(28) = -3.72$, $p = .001$. In addition, logged data shows that, on average, players in the GulliVR condition voluntarily played about twice as long in the exploration phase ($M = 11.38$ min, $SD = 4.60$) than participants using the teleportation approach ($M = 6.34$ min, $SD = 2.98$); $t(28) = -3.56$, $p = .001$. During the story-driven first part of the game, the difference in duration was not significant (GulliVR: $M = 6.82$ min, $SD = 2.73$; Teleportation: $M = 5.93$ min, $SD = 1.53$); $t(28) = -1.10$, $p = .280$.

Table 3. Mean scores and standard deviations of the custom questions (CQ) and independent samples t-test values of comparison.

	Question Item	GulliVR ($N = 15$) M (SD)	Teleport ($N = 15$) M (SD)	t (28)	Sig. p	
CQ1	I would have preferred to move through the world using another technique.	1.20 (1.66)	2.80 (2.00)	2.38	.024	*
CQ2	I think I have been walking much in the (real) room while playing the game.	4.27 (1.98)	2.33 (1.76)	-2.83	.009	*
CQ3	While playing, I wondered why I had the ability to [teleport/grow and shrink].	0.80 (1.57)	0.27 (0.59)	-1.23	.228	
CQ4	I could orient myself well in the game world.	4.60 (1.40)	3.33 (1.29)	-2.57	.016	*
CQ5	I would have liked to spend more time in the game world.	5.20 (0.86)	4.20 (1.37)	-2.39	.024	*
CQ6	From above, the world appeared to me as a miniature or toy world.	5.27 (0.96)	–	–	–	

*p <.05, ** p <.01

Further Comparisons Between GulliVR and Teleportation

Besides testing our hypotheses, our study was aimed at gaining insight into how players experience and evaluate the GulliVR navigation technique, both individually and compared to the established teleportation approach. We compared the ratings of our custom questions and found significant differences between the two groups as outlined in Table 3.

We were also interested in whether the method of navigation also influences aspects of the player experience other than presence. Hence, we analyzed group differences regarding the seven subdimensions of the GEQ. Results indicate that participants in both groups do not differ significantly regarding any of the subdimensions (all $p > .158$).

Targeting with GulliVR

We investigated how precisely players in both groups were able to "hit" predefined targets with GulliVR. Results show that, on average, they missed the center of the target by 0.10 meters ($SD = 0.04$) in room-scale metrics. For a comparison, the radius of the target was 0.25 meters, i.e., players "landed" closer to the center than to the outer perimeter, as depicted in Figure 6. Our data also indicates a learning effect: players in the GulliVR condition, who had used the technique in the previous phases of the study, performed significantly better in the targeting task ($M = 0.07$ m, $SD = 0.02$) than players who were completely new to it ($M = 0.13$ m, $SD = 0.04$); $t(22.29) = 3.86$, $p = .001$.

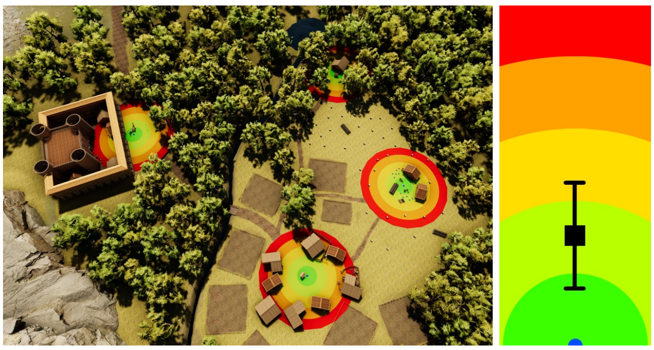

Figure 6. The targeting task from GM perspective. The circle has a radius of 0.25 meters in room scale. The illustration on the right exposes the average precision and standard deviation of all participants.

DISCUSSION

Our results confirm all three hypotheses: GulliVR navigation leads to an increased feeling of presence and makes players walk around in the room frequently without causing cybersickness. The absence of cybersickness promotes our technique to a considerable alternative for navigating a VR game world. In particular, GulliVR induces even slightly less cybersickness compared to the established teleport approach.

Our study demonstrates the major strength of the GulliVR technique: it can significantly increase the players' feelings of presence and thereby supports an intense and positive player experience. Several subscales of our presence measures support that assumption. Notably, the PQ questionnaire reveals that the experience of being able to explore the game world and interact with it is increased. We attribute these results to the fact that the natural conversion of physical steps into in-game navigation allows a more direct relationship with the virtual world. Our finding also aligns with previous research that demonstrated the positive impact of natural walking metaphors [53, 59, 66, 67]. In contrast to GulliVR, teleportation is a rather abstract, and, more importantly, discontinuous approach that potentially increases the disconnection from the virtual world.

One aspect we believe contributes to the positive presence effect is the increased physical activity of players that is necessary to move through the world. The GulliVR technique encourages players to exploit the whole space of the room-scale VR system. Indeed, according to CQ2, subjects in GulliVR mode reported the feeling of walking much in the real room, i.e., players were aware of their increased movement.

Our data also indicates that GulliVR increases players' motivation to explore the game world. First, players spent significantly more time in the voluntary exploration phase. Second, according to CQ5, players reported that they would have liked to spend more time in the game world. Furthermore, participants stated that they were able to orient themselves quite well in the game world, and much better than in the teleport condition (CQ4). Thus, as expected, GulliVR supports orientation and provides a good overview of the landscape/world.

In sum, the GulliVR navigation technique is perceived well by the players, which is also confirmed by the other custom questions. GulliVR participants did not want to have another possibility to navigate through the world (CQ1), whereas this desire was significantly higher in the teleportation group. Interestingly, in neither GulliVR nor teleportation condition did players question the way they were able to move through the game world (CQ3). In other words, although both methods are not very realistic, it is not crucial to explicitly embed these techniques in the game context, because players simply accept them as game mechanics, reminiscent of game twists such as fast travel, which is also not natural but is rarely questioned.

In GM, nearly all participants perceived the virtual environment as a toy world (CQ6). The miniaturization is due to the increased modeled eye distance, and our results confirm and extend previous research in that area [72, 51, 69].

The results also point to one important challenge when using GulliVR, namely precise targeting when switching from GM to NM. Both our observations during the exploration phase and the results of the targeting tasks indicate that players had problems "landing" exactly where they wanted to. Although players seem to get used to the aiming approach and performed better over time, we suggest that targeting should be supported by the game system to avoid frustration. Such supportive approaches and further design implications for GulliVR will be discussed in the following section.

DESIGN IMPLICATIONS

GulliVR extends the toolbox of VR navigation techniques. The section is our preliminary guideline regarding the integration of the technique into VR games and VR applications in general. Hence, we address limitations and important degrees of freedom to be considered when implementing GulliVR.

Target Acquisition

Our targeting experiment demonstrated the precision issues of players when switching from GM to NM without any additional help. Therefore, we recommend integrating supportive mechanisms to prevent players from "landing" offside. In the section *"GulliVR Navigation"*, we proposed two approaches: passive pulling and active aiming, as also depicted in Figure 2. Our testbed game utilized pulling, as the scenario was rather linear. In that case, players usually did not note that they got pulled to certain locations. However, in the explorative session, players sometimes figured out that they appeared at the same place over and over, although they initiated the transformation to NM from a slightly different place.

An even more restricting implementation of pulling would be to allow GM to NM transitions only at points of interest. Such as approach can be helpful if players have to traverse larger between-level areas without any game elements. For nonlinear games, we instead recommend the active aiming technique by projecting crosshairs onto the ground next to the player's feet. This technique allows the player to pick the precise destination location at the cost of introducing an additional UI element, i.e., the crosshairs. We assume that such a technique might slightly lower the presence but increase the perceived competence. An experimental validation of that assumption is part of our future work. Note that the proposed technique requires an adaptation for scenarios with multi-level buildings. In those cases, one possibility is to include an additional UI element (floor picker) that explicitly asks the player for the desired level.

GM Size

Game designers have the choice between predefined GM size and user-defined manual resizing. According to Kopper et al. [34], the manual approach is less effective, but might prove otherwise for certain types of games. Recall that in our scenario, we applied predefined GM size, but with dependence on the current game state. Our guideline was to enlarge players to a size where they could travel to the next point of interest within a few steps.

Resetting

GulliVR does not completely remove the restrictions imposed by the room size. Hence, game designers should think of a suited resetting mechanism for cases where players reach a physical wall and still want to move forward. GulliVR comes with a built-in reset: switching to NM, making several steps backward, and switching to GM again to overcome the distance in one step. However, such an activity often involves undesired cognitive workload and could be avoided by including other navigation facilities for resetting purposes. For instance, similar to redirected walking, one could rotate the world during NM/GM transitions such that players always move toward the furthermost wall. We propose to evaluate that technique as part of possible future work, as we assume that more studies are needed to, e.g., determine how such rotation would impact the orientation ability of players.

Modeled Eye Distance

The virtual eye separation, also called stereo base or modeled eye distance, should be always scaled in proportion to the virtual body size. Otherwise, there is a misalignment between the virtual and the physical floor, resulting in either a feeling of floating/flying (eye distance too low) or standing below the ground (eye distance too high).

Miniaturization

Developers should be aware that increasing the modeled eye distance leads to perceiving the surroundings as a toy world, which could also be an interesting game element. We observed that the effect diminishes when the scaling factor is set to extreme values (200x in our pretests), and the miniaturization impression is replaced by the bird's eye perspective, i.e., players feel more like flying. This was a surprising observation, and might also be part of future research in that area.

Embedding in Storytelling

A body of famous literature, such as *Alice in Wonderland* [8] or *Gulliver's Travels* [64], describes size alterations of the protagonists. VR games based on these stories are canonical examples where GulliVR navigation can be easily and meaningfully integrated into the storyline. On the other hand, our study shows that the technique also works without any story-related cues. Hence, both options are feasible, and the choice should depend on the actual game.

Interplay with Other Game Mechanics

GM provides an excellent overview of the current area, limiting certain quests where players have to search for a specific location. To overcome that limitation, discoverable locations could be hidden in GM and require players to explicitly switch to NM, e.g., a dungeon entry is visible only when the player is on the ground. An alternative is to cover potential points of interest in fog of war, which prevents players from gathering too detailed knowledge from above. Depending on the player task, it might be beneficial to explicitly deactivate GulliVR for certain key locations or having GulliVR only as a fast travel mechanism.

Transformation Time

Based on previous research, we assumed that a slow transformation between GM and NM would induce cybersickness. A small experiment with five participants confirmed that the transition should be executed in less than $0.005 * Scale_{GM}$ seconds and at constant speed. At lower speeds, severe cybersickness symptoms occur almost instantly. As a rule of thumb, we recommend keeping the transition always below one second. Instant transformation is also safe, but might result in a slight disorientation.

Walking Ground

Games usually rely on the ground relief to compute the player camera height, i.e., stepping on a virtual stone or hill increases the camera height. GulliVR demands certain attention at this point, as such implementations would cause a considerable amount of camera shaking while, e.g., walking over a forest in GM. To prevent that, we recommend smoothing approaches such as Gaussian blur or simple averaging, as outlined in Figure 7. Roughly speaking, such methods align with having a giant foot while being in GM.

Object Manipulation

VR games often include the task of picking up and carrying an item to a destination. If the carried object remains visible to the player, we suggest that switching to GM should also proportionally enlarge that item. However, the ability to drop objects while being in GM should be considered. In our case, the dropped object remained big, and more than once, the interaction was a source of amusement during the free exploration mode. Furthermore, a decision needs to be made whether players in GM are allowed to interact with “miniature” objects on the ground.

Closed, Sheltered Areas

GulliVR works best when players do not see a ceiling above them. Paired with a fast, but not instant, transition time between GM and NM, that restriction allows us to maximize the orientation ability of players, as demonstrated in our experiment results. Although certain exceptions, e.g., going from NM to GM while being in a house in our game, work fine, we do not recommend GulliVR for games with dominant indoor scenery. Obviously, the technique is most unsuitable for narrow, multilevel closed environments.

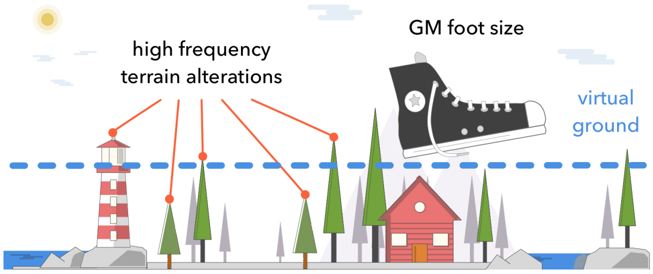

Figure 7. A virtual walking ground based on the smoothed ground relief prevents camera jittering when players walk over obstacles.

Game Genres

We consider 3D adventures and similar genres to be most suited for GulliVR, as such games usually revolve around emerging into a virtual world. Integrating GulliVR into fast-paced games that include enemy interactions, e.g., shooters, requires decisions regarding enemy behavior while the player is in GM. For instance, enemies could freeze, become invisible, or just be invulnerable. Furthermore, we encourage the integration of GulliVR into, e.g., RPGs, as a realistic alternative for fast travel.

CONCLUSION AND FUTURE WORK

Implementing navigation is one of the most compelling challenges when designing a VR game. Our presented technique is a novel possibility for traversing larger distances by enlarging the players' virtual bodies on demand. In contrast to established methods such as teleportation, GulliVR emphasizes physical walking, which leads to a significantly increased presence. Furthermore, the proportionally enlarged modeled eye distance resolves the cognitive mismatch between physical movements and visual feedback, reliably obviating cybersickness. Our experiments confirmed these assumptions and promoted the suitability of our technique for various kinds of VR games and other VR applications. In addition, the paper provided a discussion on several key features such as targeting, resetting, miniaturization, and transformation time.

Our future work will investigate these features in more detail. In particular, we will explore how GulliVR can be combined with other navigation techniques to add support for traveling in sheltered environments and to allow efficient resetting mechanisms. Furthermore, our research will tackle the question whether and how the technique can be embedded into game storytelling, both in terms of players' embodiment perception and the impression of suddenly arriving in a toy world. Related to this, it might be interesting to investigate whether users should be able to adjust their giant size scale. We also suggest an evaluation of the strengths and weaknesses of GulliVR in different game genres to create a comprehensive guideline for VR researchers and developers.

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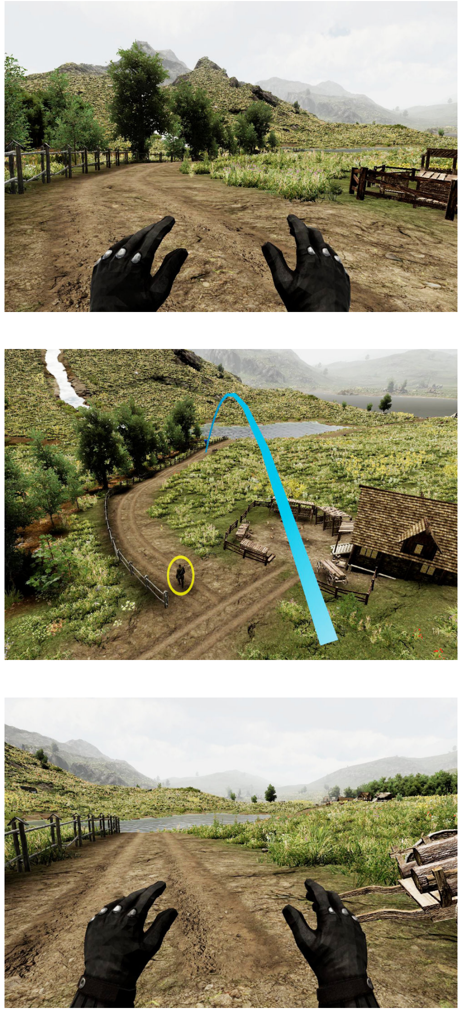

Figure 1: Navigation Technique: Start in *first-person* (1), grow to *third-person perspective* and set a navigation target (2), wait for the avatar to walk there and switch back to *first-person* (3).

Outstanding: A Perspective-Switching Technique for Covering Large Distances in VR Games

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ABSTRACT

Room-scale virtual reality games allow players to experience an unmatched level of presence. A major reason is the natural navigation provided by physical walking. However, the tracking space is still limited, and viable alternatives or extensions are required to reach further virtual destinations. Our current work focuses on traveling over (very) large distances–an area where approaches such as teleportation are too exhausting and WIM teleportations potentially reduce presence. Our idea is to equip players with the ability to switch from first-person to a third-person god-mode perspective on demand. From above, players can command their avatar similar to a real-time strategy game and initiate travels over large distance. In our first exploratory evaluation, we learned that the proposed

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KEYWORDS
Virtual reality games; navigation; fast-travel; virtual avatar; presence; world-in-miniature

*"I did not even have to think about navigating, everything was completely natural." (**P1**)*

*"I could see so much more during traveling - this invited me to explore interesting spots." (**P2**)*

*"I liked that the travel speed was limited by the avatar's walking pace; it made everything very realistic." (**P3**)*

*"When I realized that I was able to leave the path and explore the world freely on my own: that was the moment the game became so interesting to experience." (**P4**)*

*"The avatar intelligently chose to take shortcuts, this is an awesome technique!" (**P5**)*

*"This felt like being god and commanding entities, with the ability to possess them at will." (**P6**)*

*"The technique enabled me to travel large distances with one click - this was so easy and comfortable to use!" (**P7**)*

*"I always knew where I was and which path to take. The overview that I gained through traveling was excellent!" (**P8**)*

dynamic switching is intuitive, increases spatial orientation, and allows players to maintain a high degree of presence throughout the game. Based on the outcomes of a participatory design workshop, we also propose a set of extensions to our technique that should be considered in the future.

INTRODUCTION

Virtual reality allows players to explore fictive environments in an immersive and natural manner, to experience a feeling of being there, and to almost forget the real surrounding. But what does it take to realize virtual experiences of the vast and open worlds usually found in today's digital games? With continuous technical improvements such as higher display resolutions, better spatial tracking, and new rendering techniques, current game engines are capable of rendering even larger scenes despite the necessary VR overhead. However, stable frame rates and huge open environments are useless without proper techniques that enable players to freely and immersively wander through these landscapes. Natural walking using room-scale tracking is too confined by the available space. Typically used virtual locomotion techniques are either optimized for short distances, prone to cybersickness or involve visible cuts that decrease the perceived presence. To our knowledge, there is currently no available navigation approach that was specifically designed for large-distance travels and that preserves high levels of presence and spatial orientation while avoiding cybersickness.

We propose a navigation technique that fills this gap by using multiple player perspectives. Players can dynamically switch between a first-person and third-person god-mode perspective depending on the current task: If players want to explore a local spot and interact with the environment, they can use a first-person point-of-view to experience the world like they are used to. In the third-person mode, they watch and command their avatar from a bird's eye perspective, which allows them to cover larger distances with ease. We claim that this technique does not infer any cybersickness and increases the perceived presence compared to established techniques.

In this paper, we report our ongoing work on the previously described navigation approach. After realizing an implementation of the technique and a suitable test bed scenario, we have gone through an extensive participatory design phase to optimize and tweak the available parameters. The resulting prototype was evaluated in an exploratory study to gain further insights into usage patterns, problems, and necessary additions.

RELATED WORK

Most non-VR games use joysticks to control the player's avatar. Such approaches involving continuous motion are rarely transferable to VR as they tend to induce cybersickness [7]. Instead, many VR games rely on natural walking [10] to achieve natural and presence-preserving navigation. However, the confined space of currently available room-scale tracking limits natural walking to few square meters.

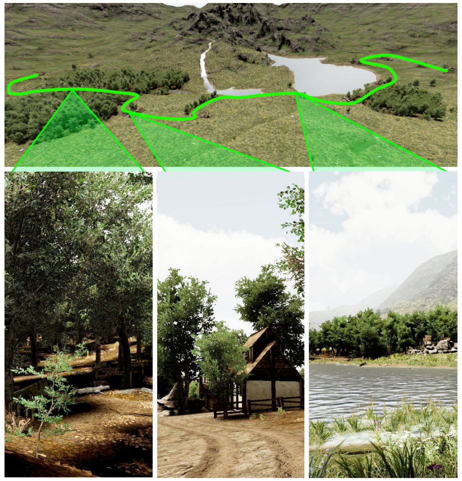

Figure 2: The medieval scenario used as testbed game. Players could follow the long path (marked in green) and search for animals at points of interest (bottom).

Figure 3: Some of the animals found along the path. *Forced Switching* is used to prevent players from missing these spots.

Recent research has attempted to overcome this limitation by extending the range of real walking to enable the player to reach further. Bhandari et al. [2] combined walking with walking in place and reported higher presence compared to traditional controller input. Another approach by Bolte et al. [3] uses the detection of physical jumping: When an acceleration and consecutive jump are detected, the resulting forward motion is augmented to travel larger distances.

In contrast to these augmented walking approaches, purely virtual navigation techniques sacrifice the advantages of natural walking to achieve unlimited traveling. The most prominent approach is the teleportation technique: players aim at an accessible destination and are directly teleported there. This approach has been shown to be superior to the traditional gamepad locomotion [5], however, the perceived presence and spatial orientation are significantly lowered by the instant relocation. Even worse, the necessity to view the target location limits the maximal distance to be traversed in one jump and vastly increases the necessary workload for larger travels or occluded areas.

One remedy for true large distance travel in VR is the concept of a world-in-miniature (WIM) [11]: a virtual three-dimensional minimap is used to move instantaneously to any point within a large and complex environment. In comparison to teleport, WIM works better with larger distances and occlusions [1]. However, it introduces the minimap as an additional artificial interface which is decoupled from the original virtual world. Since both approaches were never designed to be a perfect solution for long-distance travel, this encouraged us to develop an immersive and natural alternative.

Our approach is based on switching between first-person (1PP) and third-person (3PP) perspectives. Gorisse et al. [6] administered the perceptual differences: According to their experiments, both perspectives are able to preserve high levels of presence and agency. However, 1PP is best suited for interaction-intensive tasks and scenarios involving body ownership. In contrast, 3PP provides advantages to spatial awareness and environment perception. These findings support our idea for a navigation metaphor using 3PP for large-distance navigation and 1PP for local interaction. Gorisse et al. [6] decided to place the 3PP viewpoint directly behind the avatar. However, this is not suitable in our case as it does not improve the view distance or environmental knowledge of the user. Instead, we have decided to scale the disembodied players to giant size. By doing so, the virtual camera position is moved to a greater height and enables players to perceive the environment as a miniature world. Meanwhile, their avatar resides at his original size to the feet of the players. This approach has been shown to be uncritical regarding cybersickness and provide benefits for spatial orientation [9].

NAVIGATION TECHNIQUE

The main idea behind our locomotion technique is to switch different perspectives on demand based on the current situation. The first-person view of the normal mode (NM) is used for basic interaction and short-range exploration by physical walking within the virtual world. The travel mode (TM) is a third-person perspective for long-distance travels where players are scaled to ten times their original

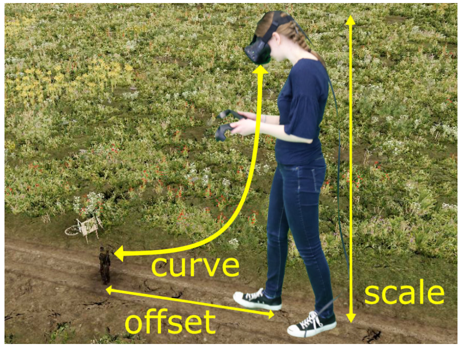

Figure 4: Transition Parameters.

Scale: The factor by which players are scaled in travel mode. (cf. Figure 5) *Proposed value: 10x*
Offset: The offset that is applied to the players' position in TM to improve visibility of the avatar and prevent a 90° angle downwards. *Proposed value: 20m which equals roughly* 45°
Speed: The total duration of the transition. *Proposed value: 0.5s*
Curve: The applied animation curve used to transform between NM and TM. We tested linear and curved transitions.

Figure 5: Different scaling factors for TM that were evaluated in the participatory design phase: $10x$, $30x$, and $100x$. Players preferred $10x$, even though this requires fixing the occlusion, e.g., of leaves.

size and see their own avatar keeping his original scale and symbolizing the players first-person position in the world. The disembodied players can command the avatar by setting navigation targets through raycast aiming (cf. Figure 1). They can decide to switch back to NM at any time to explore a specific place in greater detail. This concept uses both perspectives [6] to combine the fast and easy traveling of long distances with the possibility to explore details on demand. Due to the absence of instant relocations and artificial camera movements, we argue that this technique - in contrast to teleport and WIM - increases presence and prevents cybersickness. As positive side effect, we assume a significant gain in spatial orientation, as players are able to observe the surrounding world using a god mode and can choose an optimal path depending on this additional information.

Our proposed technique can be split into three components: NM, TM, and the transition between both states. While NM and TM only differ in the positioning of the virtual camera, the transition is more complex. It requires an optimal calibration to avoid cybersickness while preserving a consistent experience without noticeable cuts. The resulting animation depends on several continuous parameters (cf. Figure 4) that need to be tweaked accordingly to achieve the desired outcome.

Participatory Design

We executed an early participatory design phase to optimize the available continuous parameters. The 4 participants (2 female) with a mean age of 30.0 (SD = 5.83) were familiar with VR systems but not involved in this project. We asked them to test our provided scenario and give oral feedback which was used to calibrate the parameters. We followed the order given in Figure 4, starting from the most noticeable factor, and waited at least two minutes between two parameters. The result was a set of optimized parameters. At this stage, we added two extensions: *Forced Switching* and *Catching Up*. *Forced Switching* prevents players from missing out important destinations by transitioning them into NM (cf. Figure 7), while *Catching Up*, triggered by a button press, moves the player‘s camera to the current avatar position to reduce the necessary switches during longer travels (cf. Figure 6).

Exploratory Study

After the design phase, we executed an exploratory study to gather insights into how players would use our technique. This included preferences, expectations, and problems. The provided scenario was set in a fictive medieval world (cf. Figure 2) where players had to follow a long, twisted path passing several forests, lakes, villages, and mountains. The task was to find and observe different types of animals roaming specific areas (cf. Figure 3). This setting provided a suitable testbed for our navigation metaphor as it included traveling two kilometers while switching back to NM at points of interest.

The study was conducted in our VR lab and took 45 minutes on average. During the first half of the virtual travel, we encouraged the participants to give feedback. In the second part, we avoided any further conversations to allow the subjects to play undisturbed for a longer time and immerse

Figure 6: With *Catching Up*, players can close the large gap to their avatar (left) with a single button click (right).

Figure 7: If the avatar reaches an important destination, *Forced Switching* is used to switch back to NM automatically.

themselves into the virtual environment. After finishing the game, the subjects had to fill out the Presence Questionnaire (PQ) [4] and Simulator Sickness Questionnaire (SSQ) [8] to assess presence, cybersickness, and fun. The study was completed by another round of interview questions and the opportunity to share feedback, concerns or ideas regarding our approach.

Results and Discussion

In total, 8 persons (4 female) participated in our study with a mean age of 26.7 ($SD = 7.98$). All participants reported playing digital games at least a few times a month and already had used VR gaming systems before. Even though this group size is too small for a quantitative analysis, the assessed questionnaires and given oral feedback already provide important insights.

The technique was very well accepted by all players and described as *"natural" (**P4**)* and *"surprisingly intuitive"(**P5**)*. Players were able to explore the world freely and could *"reach every desired destination effortlessly"(**P2**)*. The environment was generally reported as being fun to experience and interesting to explore. This feedback reflects the high scores of all subscales from PQ (cf. Figure 9). Additionally, the results from the SSQ (cf. Table 1) suggest that using our technique causes no cybersickness.

Interestingly, the participants did not perceive the third-person avatar as their own body. Instead, they described it as an *"NPC entity"(**P6**)* controlled from a *"god-mode"(**P5**)*. However, this lack of body ownership was by no means a drawback but an opportunity for additional features such as controlling multiple entities or interacting with the world using god-powers. Additionally, players liked being constrained by the avatar as it made traveling *"a realistic and believable process"* instead of an *"artificial relocation"(**P3**)*. However, all subjects initially expected their avatar to keep on walking after switching back from TM to NM: in our implementation, the avatar is stopped immediately after switching since artificial motion tends to cause severe cybersickness.

The optimized parameters from the participatory design phase were approved by all participants. The chosen scaling factor *"balanced the spatial overview and the visibility of details"(**P1**)* and invited players to *"explore the world"* as it revealed *"interesting spots in a greater context"(**P2**)*. Even though the navigation worked best for larger distances, it *"should be completed by other techniques like the teleport for local hotspots"(**P2**)*. The only drawback of the chosen values was that the players had the same virtual height as the forest trees and ended up being surrounded by leaves. The resulting occlusion was perceived as disturbing. Possible solutions suggested by various players were to increase the scaling factor in forests, cull nearby leaves, or add a focus technology to reveal the avatar's position.

Finally, we asked the subjects for potential VR games that could profit from such controls. The answers were plentiful and ranged from exploratory adventure games to simulations like *The Sims* or role-playing games such as *The Witcher* or *Kingdom Come: Deliverance*. In general, the participants claimed a good benefit for explorations and huge open worlds but mentioned potential issues when trying to include real-time first-person actions like fights or dialogues.

Figure 8: Potential fix for the avatar occlusion through leaf-culling.

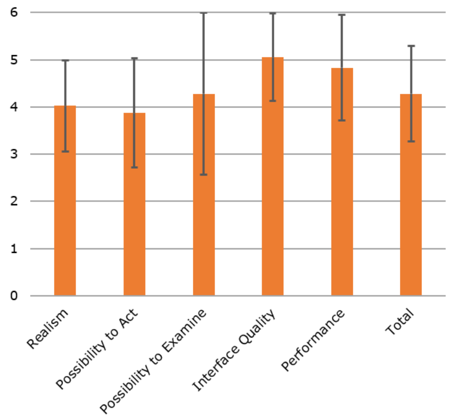

Figure 9: Mean scores and standard deviations of the Presence Questionnaire (PQ). Subscale scores range from 0 (fully disagree) to 6 (fully agree).

SSQ Dimension	M (SD)
Nausea	2.39 (4.77)
Oculomotor	7.58 (15.16)
Disorientation	10.44 (20.88)
Total	6.80 (11.58)

Table 1: Mean scores and standard deviations of the Simulator Sickness Questionnaire (SSQ).

CONCLUSION AND FUTURE WORK

We proposed a novel approach to large-distance travel in virtual environments, which uses the benefits of multiple perspectives to achieve natural and intuitive locomotion. In contrast to existing methods such as teleportation, players do not have to beam themselves hundreds of times but are able to traverse long distances with ease. Our exploratory study supports the basic assumption that this experience comes with high levels of presence, fun, and spatial orientation while completely avoiding cybersickness. As future steps, we suggest add requested features that emerged during the study. This includes a solution to the avatar occlusion (cf. Figure 8), an option to walk faster, and the use of additional navigation methods for local exploration. Our next major step is to conduct a quantitative study to compare the proposed technique against existing approaches, to point out the relevant benefits and drawbacks, and to generate a comprehensive set of design guidelines to be used by researchers and practitioners.

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Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games

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Figure 1. Our proposed navigation technique allows players to switch to a scaled third-person perspective on demand and control a virtual avatar to cover large distances in open world VR scenarios.

ABSTRACT

In virtual reality games, players dive into fictional environments and can experience a compelling and immersive world. State-of-the-art VR systems allow for natural and intuitive navigation through physical walking. However, the tracking space is still limited, and viable alternatives are required to reach further virtual destinations. Our work focuses on the exploration of vast open worlds – an area where existing local navigation approaches such as the arc-based teleport are not ideally suited and world-in-miniature techniques potentially reduce presence. We present a novel alternative for open environments: Our idea is to equip players with the ability to switch from first-person to a third-person bird's eye perspective on demand. From above, players can command their avatar and initiate travels over large distance. Our evaluation reveals a significant increase in spatial orientation while avoiding cybersickness and preserving presence, enjoyment, and competence. We summarize our findings in a set of comprehensive design guidelines to help developers integrate our technique.

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CCS Concepts

•Human-centered computing → **Virtual reality; •Software and its engineering** → *Interactive games;*

INTRODUCTION

Virtual reality allows players to explore fictional environments in an immersive and natural manner, to experience a feeling of being there, and almost to forget the real surrounding. Continuous technical improvements and faster rendering approaches make it possible to push the boundaries of VR even further and develop vast open environments that could be explored freely and immersively. However, large and detailed VR worlds require proper techniques to travel these landscapes.

Physical walking using room-scale tracking offers an intuitive and natural kind of navigation [40]. However, the available walking space is usually confined to the size of a living room. Game developers overcome this limitation by adding virtual locomotion techniques such as the prominent teleport (see Figure 5). Most of these approaches were designed for local navigation and are not ideally suited for exploring large and open worlds. Only a few exceptions exist, such as the world-in-miniature (WIM) [49], where players use a miniature model of the virtual scenario to teleport themselves to distant places. Nevertheless, this approach relies on an artificial user interface and does not provide an opportunity to explore an environment freely and continuously which potentially reduces the players' possibility to immerse themselves in the virtual world.

Our research closes the gap between local teleportation and WIM relocation by introducing a novel approach for continuous long-distance traveling. Our main idea is to switch dynamically between a first-person and a third-person bird's eye perspective on demand. The first-person mode offers a familiar experience and is used to explore the local surrounding and interact with the environment. In the third-person mode, players see and command their avatar from a bird's eye perspective, as depicted in Figure 1.

Using the correct perspective for every situation offers important benefits [15]: first-person is suited best for interaction-intensive tasks while third-person provides a better overview. We combine both perspectives to achieve an intuitive navigation approach. Moreover, we extend this basic concept by additional features to enhance the experience further: Virtual scaling of the player in third-person mode is used to improve the spatial orientation and deliver a feeling of moving through a miniature world while commanding an avatar. Additionally, we use a smooth and fast transformation between both perspectives to prevent cybersickness and to emphasize the impression of leaving and re-embodying the virtual avatar.

Our main contribution is the proposed navigation technique using dynamic perspective switching. We validate this approach by comparing it against the arc-based teleport using a 3D adventure game. Our experiments reveal significant benefits to spatial orientation and overview while preserving equal levels of presence, enjoyment, and competence. Additionally, our improvements prevent adverse effects through cybersickness. As the final step, we discuss the unique strengths and weaknesses of our proposed approach and condense these into a set of design implications that can help developers and practitioners.

RELATED WORK

Our work belongs to the virtual reality research with a particular focus on VR games and locomotion techniques. Consequently, we first introduce basic concepts and issues behind VR games such as immersion, presence, and cybersickness. Subsequently, we outline the current state of the art in VR locomotion research. Since our technique centers around the concept of perspective-switching and dynamic virtual rescaling, we also provide the necessary background to these topics.

Two concepts seem to be of utmost importance when dealing with VR applications: *immersion* [8] and *presence* [18]. To stay in line with the majority of recent research, we use the term immersion to describe the technical quality of a VR setup [6, 45]. Immersive setups can induce a feeling of being there, which is commonly called presence. This distinction is further formalized by Slater et al. [46], Lombard et al. [33] and IJsselsteijn et al. [21]. For a particular focus on locomotion-related presence, we point to the work by Slater et al. [47].

Cybersickness

A typical problem most VR applications have to tackle is the occurrence of cybersickness [29]. Even though often being used synonymously with the effect of simulator sickness [25], both are different strains of the motion sickness phenomenon [35, 20, 36]. Typical symptoms such as headaches, eye strain, sweating, nausea or vomiting arise due to a mismatch of our vestibular-ocular system.

Humans sense acceleration using their vestibular system which usually matches the sensory input gathered from the visual system [29]. In the case of a mismatch between these signals, the resulting symptoms differ in strength and form [39]. The reason for this body reaction remains unsolved, but so far three major prominent theories have been established: sensory conflict theory (most accepted), poison theory, and postural instability theory [29]. The difference between both specific strains of motion sickness was extensively explored by Stanney et al. [48]: Simulator sickness usually occurs when a simulator, typically used for pilot or astronaut training, is not correctly configured [24]. This technical problem can lead to rather mild oculomotor and nausea symptoms. In contrast, cybersickness is caused by a broad set of reasons ranging from technological issues such as flickering and lags to a wrong visual image being caused by mismatches in movement, eye distance or vergence. The results are mainly severe symptoms such as disorientation and nausea [48].

Additionally, Hettinger et al. [19] introduced the phenomenon of vection as a possible source for cybersickness. Vection is a feeling of moving that is solely induced by the visual system and usually experienced when sitting on a standing train and watching the adjacent train accelerating. This effect is supported by different factors listed by La Viola Jr [29]: the field of view (FOV) of the HMD, the optical flow rate, the degree of movement and proximity of objects. In short, close and fast-moving objects filling the player's view combined with a big field of view tend to amplify the amount of perceived vection and potential cybersickness. Consequently, Fernandes et al. [13] propose limiting the FOV to reduce cybersickness. A broader discussion about the influence of the FOV on cybersickness can be found in the work of Lin et al. [32].

Additionally, recent studies have shown that the accumulated flow over time, perceived via central and peripheral vision, forms a critical factor in the occurrence of motion sickness [31]. Instead of avoiding cybersickness at all costs, von Mammen et al. [53] showed that games with artificially induced cybersickness can still be enjoyable. This leads to the conclusion that a reduction of potential motion sickness to an acceptable level could be more favorable than limiting the opportunities of virtual reality to avoid risking any symptoms.

Locomotion

Most non-VR games use joysticks to control the player's avatar. Such approaches involving continuous motion are rarely transferable to VR as they tend to induce cybersickness [17]. Alternatively, VR games can use natural walking [40] to achieve intuitive and presence-preserving navigation. However, the confined space of currently available room-scale tracking limits natural walking to a few square meters.

Recent research focused on overcoming this limitation by extending the range of real walking to enable the player to reach further. Bhandari et al. [5] combined walking with walking in place [47, 51] and reported higher presence compared to traditional controller input. This result is in line with the work by Usoh et al. [52]: According to their research, walking is superior to walking in place, while both outperform virtual locomotion. Another approach by Bolte et al. [7] uses the detection of physical jumping: When a jump is detected, the forward motion is augmented to travel larger distances.

In contrast to these augmented walking approaches, purely virtual navigation techniques sacrifice the advantages of natural walking to achieve unlimited traveling. A typical problem that arises from the necessary decoupling of real and virtual movement is an increase in cybersickness. This is best tackled by "short, fast movements in VR (with no acceleration or deceleration)" [17], which has been confirmed by the work of Medeiros et al. [34] and Yao et al. [55]. The most prominently used navigation approach, using such short movements, is the arc-based teleportation technique: players aim at an accessible destination and are directly teleported there. This approach is superior to the traditional gamepad locomotion [14] and is actively promoted and encouraged by the majority of established VR systems such as the HTC Vive [10]. However, the perceived presence and spatial orientation are significantly lowered by instant relocations. Even worse, the necessity to see the target location limits the maximal distance to be traversed in one jump and vastly increases the necessary workload for more considerable travels or occluded areas.

Apart from virtual travel techniques, a couple of other solutions for infinite locomotion have been developed. One famous approach is the extension of available walking space by unconsciously altering the virtual movement from the real walk. Users are not able to sense slight rotations in the virtual environment leading to a feeling of walking on a straight line, whereas in reality, they are moving in circles. However, the necessary minimal turning rate leads to extensive space requirements. This impediment is the main reason why the concept of *redirected walking* [37, 38] has stayed a pure research topic despite numerous improvements [12, 16, 28].

One remedy for true large distance travel in VR is the concept of a world-in-miniature (WIM) [49]: a virtual three-dimensional minimap is shown on players' hands and can be used to move instantaneously to any point within a large and complex environment. This concept has been further refined by La Viola Jr et al. [30] to achieve a walkable minimap that is grown around the player's feet to replace the previous environment. In comparison to teleport, WIM works better with larger distances and occlusions [3]. However, it introduces the minimap as an additional artificial interface which is decoupled from the original virtual world. Since both approaches were never designed to be a perfect solution for long-distance travel, this encouraged us to develop a possible alternative.

Perspective and Scale

Our approach is based on switching between first-person (1PP) and third-person (3PP) perspectives. After early studies on the potential use of 3PP in virtual environments [43], Gorisse et al. [15] administered the perceptual differences in an extensive study: According to their experiments, both perspectives are able to preserve high levels of presence and agency. However, 1PP is best suited for interaction-intensive tasks while 3PP provides advantages to spatial awareness and environmental perception. These findings support our idea for a navigation metaphor using 3PP for large-distance navigation and 1PP for local interaction. Gorisse et al. [15] decided to place the 3PP viewpoint directly behind the avatar. However, this is not suitable in our case as it does not improve the view distance or environmental knowledge of the user. Instead, we have decided to scale the disembodied players to giant size, similar to the work by Abtahi et al. [1]. The virtual camera position is moved to a greater height and enables players to perceive the environment as a miniature world. Meanwhile, their avatar resides at his original size to the feet of the players.

Dynamic scaling of the virtual world or the player is not new and mostly used within so-called multiscale virtual environments (MSVE) [56]. Kopper et al. [26] used MSVEs to explore the inner organs of virtual human bodies and reported that automatic scaling outperforms a manual-chosen scaling factor regarding usability. Similarly, Argelaguet et al. [2] emphasized the importance of automatic scaling speeds and optimized stereoscopic rendering parameters to minimize adverse side effects such as diplopia or cybersickness. While MSVEs use different scaling factors to access distinct observation levels within their virtual environment, our technique focuses on the locomotion aspect and only resides on the scaling as a means to improve visibility and overview. In this manner, the closest resembling approach is the GulliVR technique by Krekhov et al. [27] that focused on full-body scaling in the first-person perspective. One widely proposed request from the CHIplay-community was to combine this approach with perspective-switching to overcome the limited field of use and to decouple avatar and player. This wish was a major motivation in developing our presented technique.

A core aspect of our idea is a bird's eye view on a miniature world. Following previous work, we decided to scale the stereo camera separation accordingly to the rest of the body. While smaller variations of this virtual eye distance do not have any measurable impact on size judgments [4], larger differences lead to a *false eye separation* [9]. The result is an altered size perception that produces the desired miniature world effect. Additionally, the resulting impression closely matches the perceived virtual movement that the scaled players experience and has been shown to avoid inducing cybersickness [27].

Figure 2. ***Normal mode*** **(left) and** ***travel mode*** **(right): In** ***normal mode (NM)*** **(left), players use their virtual hands to interact with the environment. Upon switching to travel mode (TM) on demand, the players control their avatar from a third-person bird's eye perspective.**

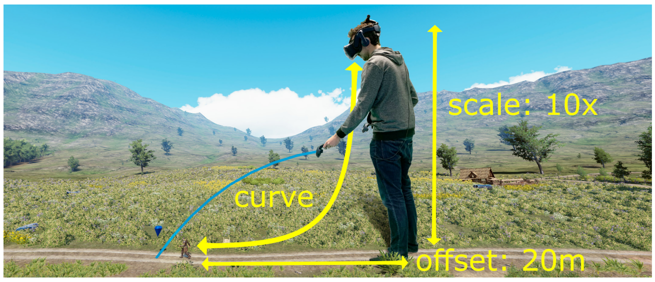

Figure 3. The different transition parameters that were used to realize a continuous perspective switch and convey the feeling of embodying or disembodying the avatar.

NAVIGATION TECHNIQUE

The main idea behind our locomotion technique is to switch between different perspectives on demand based on the current situation. In normal mode (NM), players perceive their surrounding from a first-person point of view. This perspective is used for short-range exploration by physical walking, detailed observation of local points-of-interest, and basic interactions such as picking up objects. In travel mode (TM), players leave their avatar behind and are scaled to a third-person bird's eye perspective. The virtual avatar is displayed at the players' feet symbolizing their original first-person position in the world. This view allows the disembodied players to observe the surrounding area from an elevated view and to command their avatar by setting navigation targets using raycast aiming (see Figure 2). In TM, the players are completely decoupled from their avatar and are able to explore the world independently. Each perspective has benefits and drawbacks [15]: Third-person is excellent for environmental perception while first-person outperforms in interaction-intensive tasks. Through dynamic perspective switching, we combine the strengths of both views and achieve easy traveling and superior overview with local exploration and interaction on demand.

Our technique can be split into three components: normal mode, travel mode, and the transition between both states. We emphasize a proper design of such transitions, as they contribute to the players' spatial orientation and should not induce cybersickness. The naive approach would be an instantaneous switch between both perspectives [17]. However, this contradicts the primary goal of our approach to eliminate the immediate relocations known from arc-based teleport that could lead to disorientation. Instead, a fast automatic camera translation is used, as earlier work [27, 17] showed that fast and brief movements do not induce cybersickness.

Additionally, we extend the dolly-shot-like animation to improve the impression of embodying or disembodying the avatar. Early implementations kept the virtual position of the enlarged players so that they were located right above their avatar. However, this forced them to look straight down to see and command their character. A viewing angle of nearly 90° is not only putting a strain on the human neck but also leads to a blurry vision through the headset as less pressure is applied to keep it tightly in place. Instead, we decided to add a translation backward to achieve a comfortable 45° viewing angle after switching to TM. Furthermore, a curved animation between both states emphasized a *horizontal disembodiment* followed by a steeper vertical growth (see Figure 3). Early testers collectively approved this design decision as it felt more natural and matched the intended experience. As final extension, we implemented a previously requested feature: The possibility to speed up the avatar's movements to reduce the travel time.

EVALUATION

We conducted a study to evaluate our proposed navigation technique. In this process, we designed a virtual environment with several square kilometers in size suited for testing large-scale locomotion and used it to compare the method against the most common and established alternative: the arc-based teleport. We were especially interested in how players would use the different mechanisms and how these would perform regarding performance, usability, orientation, and cybersickness.

Research Questions and Hypotheses

Our main goal is to explore the difference between the two techniques. Since our approach is novel, our priority is to determine if players can complete all tasks regardless of the used locomotion approach. Furthermore, we are interested in whether there are any differences regarding the perceived presence, enjoyment, and competence. A particular focus is placed on the perspective-switching as it is a unique feature of our technique and has not yet been used for navigation approaches. Additionally, we hypothesize that our short and smooth animation curve, coupled with correctly altering the modeled eye distance, prevents the occurrence of cybersickness. Finally, we assume that the virtual scaling leading to an increased view height, provides significant advantages to spatial orientation and overview, as players can see much more and further. To summarize, our hypotheses and research questions are:

- H1: The perspective switching provides significant benefits to spatial orientation and overview.
- H2: The proposed navigation through perspective-switching does not induce cybersickness.
- RQ3: How do players perceive the perspective switch? Are they able to use this technique intuitively?
- RQ4: Are there any differences between both approaches in terms of perceived presence and enjoyment?
- RQ5: How does our navigation technique perform regarding task completion and playtime against the arc-based teleportation?

Figure 4. Overview of the used scenario, including all important points of interest. From left to right: players follow on a path (Q1), meet a knight (Q2), destroy runes (Q3), and activate stones (Q4). The locations of all seven runes are marked as red dots.

Scenario

The game used to compare the different navigation techniques is realized using the Unity3D game engine [50] and is set in a fictive, historical world including some fantasy aspects. The environment is a massive plateau-like scenery with multiple forests, lakes, and medieval towns. Everything is surrounded by a mountainous hinterland to achieve a restricted and enclosed play area. A long, wide, and twisted path connects all relevant locations and serves as the main point of orientation (see Figure 4). To use the different navigation techniques to a full extent, this path with adjacent points of interests is chosen to cover an extensive length of more than two kilometers. The main character, portrayed by the players, is a wandering mercenary and adventurer who just seeks the next unexpected incident. In the chosen scenario, the players are given the task to follow the path (**Q1**) that ultimately leads to the largest settlement on the map. However, after a short walk of about 150 meters, the players reach a forlorn farmhouse and a knight waiting for them. The knight asks the players to help him with a bigger quest: they have to destroy a red glowing rune floating above an obelisk next to the NPC (**Q2**). A harmless rabbit sits nearby and is under a spell from the rune. After the rune is picked up by the player, it dissolves, and the rabbit is freed. This first interaction allows the subjects to try out object manipulation through virtual grabbing. The knight asks the players to continue saving animals by following the path and destroying all other runes they encounter during their journey (**Q3**). In total, the game features seven distinct runes, each surrounded by different animals. This task is the central part of the quest and involves local object manipulation as well as large-scale navigation and long-distance orientation.

The last rune is located right in front of the large settlement serving as the final destination and floats in the middle of a circle of seven obelisks. After this last rune is destroyed, the knight reappears and asks the players to help him for the last time: They have to activate the seven obelisks surrounding them (**Q4**). To complete this last local task, the players have to approach each obelisk - usually by just stepping forward - and press their hand on the stone until a ring of engraved runes lights up. This task combines first-person interactions with short-range navigation. After activating all obelisks, the knight hands a sack of gold to the player and the game is completed.

Figure 5. Player's perspective in the two study conditions: arc-based teleport (left) and perspective switching (right).

Procedure and Applied Measures

We conducted a between-subject study splitting the group of participants randomly in two groups, each using either the arc-based teleport or our technique as navigation concept. This approach was chosen to avoid adverse sequence effect from repetition as one of the central use-cases for our technique is the exploration of unknown large-scale environments. The study was conducted in our VR lab using an HTC Vive Pro Wireless setup and took 50 minutes on average. We began by informing the participants about the overall procedure and administered a general questionnaire to assess gender, age, gaming behavior, and prior VR experience. Additionally, we assessed the ability to get immersed into games, books, or movies, by administering the Immersive Tendencies Questionnaire (ITQ) [54] consisting of the four subscales *involvement*, *focus*, *games*, and *emotions*. Finally, we introduced the subjects to the HTC Vive Pro and helped them to adjust the headset to their needs.

The game was preceded by a tutorial guiding the players through every critical aspect of VR games in general and our testbed scenario in detail. It included navigation-independent parts such as walking naturally in a room-scale environment or using the trigger buttons to grab and release objects. Additionally, the subjects were introduced to the particular navigation technique and had to use it to reach specified targets in the virtual world. After completing the tutorial, subjects were placed into the actual testbed game and given the main task. We logged all durations, interactions, and distances throughout the playthrough. Upon completion of the final quest, the players were asked to remove the head-mounted display.

As the final step in this study, we administered a series of questionnaires regarding the subjects' experiences. In order to assess the feeling of presence, we relied on two different questionnaires. The Igroup Presence Questionnaire (IPQ) [44] focuses on general presence and contains one single item regarding the perceived general presence ("*In the computer-generated world, I had a sense of 'being there'* "), as well as the three subdimensions *spatial presence*, *involvement*, and *experienced realism*. For all of these items, participants had to rate statements on a 7-point Likert scale (coded 0 - 6). The Presence Questionnaire (PQ) [54, 11] focusing on interaction-related presence was used to determine the influence of the chosen navigation technique. It includes the items *realism*, *possibility to act*, *quality of interface*, *possibility to examine*, and *self-evaluation of performance* (coded 0 - 6). In order to measure the intuitiveness of the controls, we further administered the Player Experience of Need Satisfaction (PENS) [42] questionnaire with the subscales *autonomy*, *competence*, and *intuitive controls*. Additionally, we included a single subscale of the Intrinsic Motivation Inventory (IMI) [41]: *interest/enjoyment* (coded 0 - 6).

Finally, we used the Simulator Sickness Questionnaire (SSQ) [22] to examine whether the game in general or one of both navigation techniques might have caused cybersickness. The SSQ consists of the three subscales *nausea*, *oculomotor*, and *disorientation* using a scale from 0 (none) to 3 (severe). The questionnaires were completed by several custom questions (coded 0 - 6) to gain essential insights into how the participants used the different navigation approaches (see Table 3). The study was finished by semi-structured interviews to allow all participants to share their experiences.

RESULTS

In total, 30 persons (9 female, 21 male) participated in our study with a mean age of 27.2 ($SD = 11.09$). Most participants reported playing digital games at least a few times a month. Even though the majority (83%) had already used VR systems before, only 43% of those reported using VR regularly. Therefore, the group of participants could be split nearly evenly into three categories: newcomers, occasionally users, and experienced VR gamers. All subjects were randomly split into two groups, one for each condition. These groups did not differ significantly regarding the distribution of VR experience, age, gender, or immersive tendencies ($t = 0.44, p = .662$).

To answer our research questions and evaluate the hypotheses, we compared the results of all measures between the two conditions. To ensure the necessary requirements for parametric calculations, we tested for homogeneity of variances using Levene's and for normal distribution with Kolmogorov-Smirnov tests. If the requirements were not met, we replaced independent sample t-tests through Mann-Whitney U tests.

Questionnaires

In H2, we assumed that our technique avoids inducing additional cybersickness. The resulting weighted scale scores of the SSQ are depicted in Table 2. It is to note that, concerning to reference values by Kennedy et al. [23], all values are very low and indicate no problems with cybersickness in both conditions. Even though most dimensions show slightly better results for our approach in comparison to the control group, these differences are not significant (all $p > .393$).

In order to assess the research questions, we measured the perceived presence, competence, and enjoyment between the two study conditions. The resulting scores and independent sample t-tests are shown in Table 1. The two presence questionnaires do not indicate any significant difference between our approach and the teleportation technique. However, two subscales stand out: players using the teleport tend to experience more involvement, while subjects in the other group report slightly more possibilities to act (both $p < .100$). Furthermore, most subscales show slightly better values for the teleport group. Similarly, the IMI questionnaire does not show any significance regarding the perceived enjoyment despite a slight tendency towards the established teleportation approach and very high values for both groups in general. Finally, the analysis of the PENS subscales reveals that both navigation approaches are perceived as reasonably intuitive. Nevertheless, the basic teleportation significantly outperforms the more complex perspective switching regarding the intuitiveness.

Custom Questions and Logging Data

Apart from using standardized questionnaires to compare both groups, we assessed several custom questions to gain further insights into how players experience our technique. These questions covered intuitiveness, usability, orientation, and perspective-switching. The results shown in Table 3 indicate a significant difference in spatial orientation: Participants using our presented approach reported being able to orient themselves far better and needing less time to recover from relocations. Additionally, the questions reveal several interesting trends between both groups.

We logged all relevant data that occurred during the play sessions (see Figure 6). In comparison to the teleport group, players using our technique played 66% longer on average ($t(28) = 6.00, p < .001$). This extended game time was mainly used to navigate in TM as the subjects played almost two-thirds of the complete game in third-person. One aim of our

Table 1. Mean scores, standard deviations, and independent samples t-test values of the iGroup Presence Questionnaire (IPQ), the Presence Questionnaire (PQ), the Intrinsic Motivation Inventory (IMI) Questionnaire, and the Player Experience of Need Satisfaction (PENS) Questionnaire.

	Outstanding ($N = 15$)	Teleportation ($N = 15$)			
	M (SD)	M (SD)	t (28)	p	
PQ (scale: 0 - 6)					
Realism	4.12 (0.93)	4.05 (0.92)	0.23	.824	
Possibility to Act	4.28 (0.65)	3.87 (0.62)	1.79	.084	
Interface Quality	4.53 (0.75)	4.69 (0.79)	-0.55	.586	
Possibility to Examine	4.31 (1.00)	4.71 (0.75)	-1.24	.225	
Performance	4.47 (1.23)	4.90 (0.74)	-1.17	.252	
Total	4.29 (0.62)	4.31 (0.55)	-0.08	.935	
IPQ (scale: 0 - 6)					
Spatial Presence	4.47 (0.60)	4.53 (0.89)	-0.24	.812	
Involvement	3.23 (1.31)	4.18 (1.31)	-1.99	.057	
Realism	2.57 (1.05)	2.60 (0.87)	-0.10	.925	
General	4.00 (1.25)	4.73 (1.10)	-1.70	.100	
IMI (scale: 0 - 6)					
Interest/Enjoyment	4.63 (0.74)	4.93 (0.96)	-0.96	.345	
PENS (scale: 0 - 6)					
Autonomy	2.87 (0.85)	3.49 (1.46)	-1.43	.165	
Competence	3.91 (1.33)	4.82 (1.24)	-0.47	.640	
Intuitive Controls	4.82 (0.60)	5.64 (0.48)	-4.14	.000	**

*p <.05, ** p <.01

Table 2. Mean scores and standard deviations of the Simulator Sickness Questionnaire (SSQ).

SSQ Dimension	Outstanding M (SD)	Teleport M (SD)
Nausea	7.00 (8.43)	14.63 (33.02)
Oculomotor	21.22 (16.26)	20.72 (21.91)
Disorientation	25.06 (21.91)	25.98 (37.89)
Total	19.95 (14.87)	22.94 (32.63)

proposed approach was to enable longer and fewer aiming operations using raycast arcs. The result is a significant reduction in target aiming by 57% in contrast to the control group ($t(16.63) = -4.72, p < .001$). In return, these saved interactions are replaced by the necessary switches between NM and TM. In sum, there is no significant difference in total user interaction count ($t(28) = -0.88, p = .388$). However, the type of aiming operations being used differs significantly: Players in the teleport-group mainly used medium-range teleportations exceeding the room scale-scope of two meters but mostly staying below 40 to 50m at max. In contrast, our navigation technique enabled players to shift a huge amount of these medium-range arcs to a few long-distance travels. This advantage does not transfer to very near targets. In this case, the necessary aiming operations are nearly equal between both groups. Finally, we assessed the distance players walked in the real world while playing. While both study groups performed equally concerning the active walking in the first-person perspective ($t(28) = -0.67, p = .506$), i.e. approaching a rune, players using perspective switching walked 60% more while commanding their avatar in travel mode ($t(28) = 3.31, p = .003$). This closely reflects the results of CQ6.

DISCUSSION

RQ3: *How do players perceive the perspective switch? Are they able to use this technique intuitively?*

In general, most participants approved using different perspectives to experience the world from various views (CQ1). These were often described as *"impersonating the avatar"(**P18**)* versus switching to a *"god-mode"(**P22**)* and guiding a protégé through the world. The general concept of dynamic perspective switches was understood intuitively and did not confuse the subjects at all (CQ11). Instead, players appreciated the *"balance between long-distance overview and local detailed exploration"(**P5**)*.

One challenge our proposed technique introduces is the increased number of control mechanisms. In contrast to the teleport, our approach uses a second button to switch perspectives and an optional third control to speed up the travel process through running. These more complex interactions are one possible reason for the results from the PENS subscales and the custom questions. Subjects generally rated our approach as being less intuitive (CQ2) and reported more problems with the controls (CQ3). Especially new players stated that it *"took some minutes not to confuse the different buttons anymore"(**P9**)*. Nevertheless, a majority of players still reported being able to reach every destination easily (CQ4) after getting used to the technique.

H1: *The perspective switching provides significant benefits to spatial orientation and overview.*

In TM, most participants perceived the environment as a toy world (CQ9). This perspective was generally appreciated (CQ10) as it placed the local surrounding *"in greater context"(**P28**)* and invited players to *"explore the world"(**P2**)*. This

Table 3. Mean scores and standard deviations of the custom questions (CQ) and independent samples t-test values of comparison.

	Question Item	Outstanding M (SD)	Teleportation M (SD)	*t* (28)	Sig. *p*	
CQ1	I would have preferred to move through the world using another technique.	3.27 (2.28)	3.60 (2.06)	0.42	.678	
CQ2	I think the navigation technique is intuitive.	4.00 (1.46)	4.60 (1.45)	1.13	.270	
CQ3	I had problems with the supplied controls.	2.20 (2.08)	1.00 (1.36)	-1.87	.074	
CQ4	It was easy to reach the next destination.	4.73 (1.49)	4.87 (1.46)	0.25	.806	
CQ5	I would have liked to have more variety during the journey.	3.73 (1.67)	3.07 (1.87)	-1.03	.312	
CQ6	I felt very active while playing.	4.07 (1.62)	3.27 (2.09)	-1.17	.251	
CQ7	I could orient myself well in the game world.	5.07 (0.88)	3.67 (2.02)	-2.46	.024	*
CQ8	After each relocation, I needed a moment to orient myself.	1.13 (1.73)	3.80 (1.61)	4.37	.000	**
CQ9	From above, the world appeared to me as a miniature or toy world.	4.60 (1.60)	–	–	–	
CQ10	I liked the ability to experience the world from above.	4.73 (1.33)	–	–	–	
CQ11	The perspective-switch confused me.	0.67 (1.45)	–	–	–	

*p <.05, ** p <.01

feedback fits the results of CQ7, revealing significant advantages to spatial orientation. Furthermore, the applied transition animation between TM and NM helped participants to preserve their cognitive map of the surrounding and reduced the necessary reorientation time after each switch (CQ8). These findings illustrate the most important advantage of our proposed technique: players can coordinate themselves better in a vast open world while avoiding to induce confusion through instant teleportation.

H2: *The proposed navigation through perspective-switching does not induce cybersickness.*

The results from the SSQ indicate that our technique does not negatively affect players in terms of cybersickness. Even though our approach includes an automated virtual movement that contradicts the signals from the vestibular system, this does not cause any symptoms. This positive finding is in line with earlier work [27, 17], emphasizing the importance of short and fast movements. Additionally, we eliminate any side effects arising from the altered perception in TM by scaling the virtual eye distance accordingly to the body size.

RQ4: *Are there any differences between both approaches in terms of perceived presence and enjoyment?*

In general, the two navigation techniques did not differ significantly concerning presence. However, the teleport was mostly rated slightly higher than our proposed approach, which is especially true for the IPQ subscale *involvement*. This result fits the general feedback: Players did not have the feeling of controlling their avatar from a third-person perspective but felt like *"disembodied beings guarding a traveler on his path"(**P24**)*. The results from PQ and IPQ and the verbal feedback show that the participants were less involved while using the TM to travel through the world.

Even the best interaction technique will never be adopted in games if it does not provide a compelling and fun experience. On first sight, the *interest/enjoyment* subscale of the IMI questionnaires reveals slightly lower results for the perspective switching approach in comparison to the teleport. However, when comparing the techniques more closely, two aspects become clear: First, the general scores for both groups are very high, and subjects in the lower rated Outstanding-group played roughly 66% longer. Together, these findings illustrate that the proposed approach preserves nearly equal levels of enjoyment despite a significantly extended playtime.

RQ5: *How does our navigation technique perform regarding task completion and playtime against the arc-based teleportation?*

All participants were able to complete the presented tasks and ultimately finish the game. However, subjects using our proposed navigation technique needed significantly more time for the same quests. Most of this overhead is due to the natural avatar walking speed: Even without any pause or switch to NM, the virtual avatar would need nine minutes of continuous walking or four minutes of running to reach the final destination. This difference in playtime does not necessarily imply a worse performance, as the game did not issue a time-relevant task. Instead, players were free to travel the world at their own speed. However, most subjects still requested either faster travels or more varieties during the journey: The presented scenario did not include enough point of interest for 15-minute

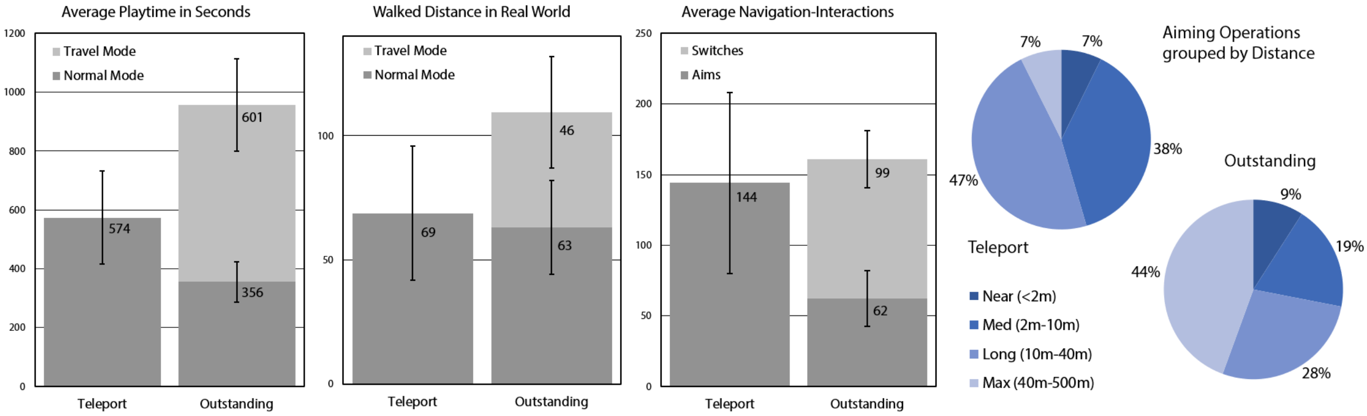

Figure 6. Results from the data logged during the play sessions. From left to right: The difference in playtime for both study groups in seconds; The average distance (in meters) players walked in the real room; The difference in navigation-relation interaction count between both study groups; The distribution of aiming operations based on distance.

Figure 7. Our proposed navigation technique performed differently depending on the distance: When traveling short distances (left), the overhead from switching perspectives outperformed the advantages. Longer travels (right) could be achieved through a single click.

gameplay. We propose to enrich the virtual world through interesting spots that make traveling a compelling experience.

One of the minor motivations to develop this navigation alternative was to reduce the large number of aiming operations that are necessary when using the teleport to traverse long distances. This goal was only partly fulfilled: For small distances, e.g., reaching a rune nearby, the perspective-switching technique did not lower the necessary aiming operations (see Figure 6, right) but imposed a minor overhead through the necessity to switch between NM and TM. We, therefore, conclude that our approach should be accompanied by an alternative fallback technique such as the teleport for very short travels. Nevertheless, the analysis reveals a major reduction of raycast-arcs in the medium-range between $2 and 40 meters$ that were replaced by fewer very long travel operations (see Figure 7). This finding underlines our initial assumption: the elevated point of view enables players to aim further and travel large distance with the ease of one command.

DESIGN IMPLICATIONS

The proposed navigation technique introduces dynamic perspective switches and extends the collection of the existing locomotion approaches for VR. This section presents a set of design implications regarding the use of our approach for VR games and applications.

Combination with other Navigation Techniques

One central goal of our proposed technique was to make travels easier and reduce the necessary effort of multiple teleportations. The study undermines the benefits of perspective switching for long distances. However, the necessary interactions add additional overhead for local areas. Therefore, we propose to accompany our approach through an additional navigation technique for short ranges, e.g., the teleport.

Choosing the Parameters

In our early design phase, we administered multiple variants of the parameters, such as TM scaling size, transformation curve, and horizontal offset. Even though these values proved to be optimal for our setup, other use cases could potentially make adjustments necessary.

- Size: In our scenario, we used a predefined scale of $10x$ to preserve most details while still benefiting to a general overview and better aiming. Participants generally appreciated this balance, even though it introduced additional challenges, i.e., avatar visibility in dense forests. A possible solution would be to add user-defined sizes, though these introduce additional degrees of freedom and generally perform worse than predefined values [26].
- Transformation: The transformation between NM and TM should be chosen fast enough to avoid inducing cybersickness and slow enough to convey the feeling of embodiment. In our early design phases, values around half a second were rated best. Additionally, a curved transformation (see Figure 3) was preferred over a linear movement and growth, as it felt smoother and more natural. Another critical aspect to a successful perspective switch is the correctly modeled eye distance. Misalignments in the so-called stereo base easily lead to strong symptoms of cybersickness.
- Horizontal offset: Initially, we used a linear vertical growth and placed the avatar right to the players' feet. However, looking straight down induces severe strain on the users' necks and often leads to blurry vision as the HMDs are not entirely fixated. Instead, we propose an additional horizontal offset backward (see Figure 3) so that the players can see their avatar at a comfortable 45°angle.

Closed Areas and Vertical Level Design

Naturally, our proposed technique does not work very well with closed ceilings as players are scaled to a bird's eye perspective and would clip through the roof while switching to TM. However, this problem is solvable for environments that are not restricted to indoor areas, such as caves. In the popular case of a house in an open-world scenario, it would be easy to hide the roof or parts of the walls while the players are in TM. This tweak would enable them to control their avatar in the house even for multi-story buildings while standing outside of the house and 'looking' through the walls.

Catching Up

Many participants suggested an additional control mechanism to catch up on the avatar. Usually, they sent him to a far-away target and had to switch between TM and NM regularly to accompany him during the journey. Since this provided an unnecessary overhead, they wished to be able to skip ahead and close the gap between the player and the avatar without switching perspectives. However, overuse of this artificial transition process could easily evoke cybersickness and should be used cautiously and sparsely.

Avatar Visibility

In areas like dense forests, players sometimes lost sight of their avatar due to occlusions by obstacles, such as trees or rocks. This made it hard to set proper navigation targets and follow the requested path. This drawback could be solved by culling or fading occluding objects or highlighting the avatar with an outline. Another solution would be to increase the virtual scaling of the travel mode.

Higher Point of View

While providing superior orientation and overview, the higher point of view in TM raises additional design challenges as well. The player could easily get spoiled from seeing too far ahead. This issue could be tackled by various possible solutions, e.g., placing natural obstacles such as mountains or using artificial techniques like the fog of war.

Providing Variety during Travel

One of the biggest requests to make our approach more compelling was the variety during longer journeys. Players had to wait for their avatar to reach his target and had quickly seen everything of their surrounding. Usually, digital games try to keep the players engaged by introducing new events regularly. In our case, a walk of two to three minutes is likely too long to preserve or increase the perceived enjoyment. Therefore, we propose to add additional incidents, either first-person encounters that force the players to switch back to NM or special actions that can be completed while waiting for the avatar, e.g., removing road barriers that stop the avatar from reaching his target. Such interactions could provide novel game mechanics and possibilities.

Novel Player Experiences

Even though the participants intuitively understood the concept of switching between the two perspectives, they commonly reported not having the feeling of controlling their own avatar. Instead, it was perceived more as a protector-protégé-relationship: The players controlled an avatar and could possess him whenever necessary. This experience is basically a flipped understanding of the underlying perspective-switch and could be used as a novel game mechanics, e.g., by controlling multiple characters at once. Additionally, the participants emphasized the importance of creating coherence between both perspectives to achieve a plausible transition.

Another interesting side effect of our approach is the impression of a miniaturized world. The proportional increase in modeled eye distance leads to perceiving the surrounding as a toy world, which allows equipping players with respective "godlike" abilities, such as increased strength. One possible application would be special TM interactions: For instance, certain obstacles, e.g., logs or boulders, could be too heavy for the first-person character and would need to be lifted in TM.

Possible Applications

We asked the participants to name potential games that would profit from our navigation approach. The most commonly named genres were adventures, role-playing games, and strategy games. We consider that especially slow titles relying on huge open worlds are suited best. In general, the perspective switching is too slow for fast-paced gameplay, as in first-person shooters. Apart from VR gaming, our proposed technique could provide essential benefits for scenarios requiring spatial orientation. Examples for such applications are large VR exhibitions or environmental visualizations.

CONCLUSION AND FUTURE WORK

The variety of established navigation techniques for virtual environments is immense. Nevertheless, there is currently no perfect approach for compelling and continuous travel over large distances. Our presented technique is a novel alternative based on dynamic perspective switching. Players can interact with the world on a local scale and switch to a third-person travel mode on demand. In contrast to the prominent teleport technique, our approach increases spatial orientation in large worlds while avoiding cybersickness and preserving high levels of presence, competence, and enjoyment. Our experiments showed that players generally liked the idea of the dynamic switching between different perspectives and that they were able to use the technique without major problems. Additionally, we summarized the key insights from the various measures and verbal feedback into a set of comprehensive design guidelines.

In our future research, we will focus on improvements and applications of our technique. A special focus will be placed on altering the approach for additional use cases, such as indoor traveling. Another interesting research question that could provide essential insights towards playing multiple characters at once, is the relationship between the players and their avatars. Furthermore, we suggest to combining Outstanding with alternative techniques for close-range navigation. Finally, we propose to investigate the potential use cases of our technique for different game genres and VR applications in general.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	**Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games** *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put...": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games

Sebastian Cmentowski, Fabian Kievelitz, and Jens Krüger. 2022. Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games. In *Proceedings of the ACM on Human-Computer Interaction*, 6, CHI PLAY, Article 246, (October 2022), 24 pages. DOI: 10.1145/3549509.

Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games

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Fig. 1. Our proposed navigation technique accelerates users' physical steps to traverse larger distances. The novel tunnel concept prevents cybersickness by shielding users from excessive visual flow. Windows in the tunnel's walls provide a direct view of the augmented movement.

The size of most virtual environments exceeds the tracking space available for physical walking. One solution to this disparity is to extend the available walking range by augmenting users' actual movements. However, the resulting increase in visual flow can easily cause cybersickness. Therefore, we present a novel augmented-walking approach for virtual reality games. Our core concept is a virtual tunnel that spans the entire travel distance when viewed from the outside. However, its interior is only a fraction as long, allowing users to cover the distance by real walking. Whereas the tunnel hides the visual flow from the applied movement acceleration, windows on the tunnel's walls still reveal the actual expedited motion. Our evaluation reveals that our approach avoids cybersickness while enhancing physical activity and preserving presence. We finish our paper with a discussion of the design considerations and limitations of our proposed locomotion technique.

246

CCS Concepts: • **Human-centered computing** → **Virtual reality**; • **Software and its engineering** → *Virtual worlds software*; Interactive games.

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1 INTRODUCTION

Walking is of central importance in our daily lives. We visit friends, go to work, or hike in the nearby forest — for most of our activities, we need to travel to a different location. Also, walking is one of the most effective ways to keep us healthy and active. All this sums up to an average walking distance between four and eight kilometers every day [5]. The same also applies to virtual reality, which reflects or even extends the real world. Whether it is an engaging game, geographical visualization, or educational lesson, most immersive experiences require the users to travel between distant points of interest. Despite decades of research on virtual locomotion techniques, real walking is still considered the gold standard. It not only feels most natural to users but also offers a range of valuable benefits, including an increased physical activity [21], the avoidance of cybersickness [71], and a superior spatial orientation [72].

The available tracking space of room-scale VR systems is usually highly limited. Living room setups, in particular, rarely exceed a few square meters in size. This technical constraint severely limits the usefulness of real walking and increases the risk of collisions with physical obstacles. Therefore, past work presented different approaches to increase the available walking range, such as augmenting users' steps [41, 98]. Increasing the movements in the virtual world allows users to travel larger scenarios fast and effectively [98]. However, the necessary transitional gains also introduce a deviation between real and virtual locomotion, which is a typical source of cybersickness. Also, this approach would augment otherwise unperceived motions, such as head bobbing or tracking errors. Therefore, the *Seven League Boots* concept by Interrante et al. [41] limits the transitional gain to the users' forward movement alone. Whereas this improvement effectively reduces cybersickness through head bobbing, previous studies highlighted several other remaining issues that diminish the practical applicability of this technique.

Firstly, the necessary detection of the users' intended movement direction often remains challenging in practice [2, 97]. Also, a clear distinction between augmented traveling and local navigation is crucial, as scaling stationary head movements is known to cause disorientation and cybersickness [101]. Furthermore, translational gains were repeatedly shown to reduce navigational accuracy and increase the necessary workload [2, 19, 61, 102]. Finally, cybersickness remains a severe issue. Even after eliminating any unwanted sideways movements, accelerated physical walking still increases the perceived visual flow in the entire field of view. Consequently, past research demonstrated a direct correlation between the applied gain factor and the severeness of cybersickness symptoms [88]. In sum, augmented walking in the current form was rarely tested with gain factors exceeding $10x$. Instead, Abtahi et al. [2] suggest limiting translational gains to $3x$ at most. This constraint severely limits practical applicability for larger scenarios, particularly in combination with typically restricted play areas.

Our research addresses the issues above by introducing a novel accelerated-walking approach for virtual scenarios. The proposed navigation concept prevents cybersickness by vastly reducing the perceived visual flow from the augmented forward movement. Also, our technique avoids the loss in accuracy by restricting the accelerated travel to a fixed path. Finally, our design makes it easy to distinguish clearly between local walking and long-distance navigation. The core element of our prototype is a virtual tunnel providing an easy and short way of traveling along a direct route between the users' current position and a predetermined target location (see Figure 1). This tunnel appears to span the entire length to the navigation goal when viewed from the outside. In contrast, the tunnel's interior is just a fraction as long to enable the users to traverse it easily by real walking. For instance, a tunnel with a length of $75m$ shrinks to $2.5m$ physical walking distance when applying a gain factor of $30x$. We achieve this impression by combining multiple concepts, such as portals for the tunnel's entry and exit.

As the users walk through the tunnel, their forward movement is scaled so that they reach their target position when leaving the compressed inner tunnel. Nevertheless, this augmentation stays primarily unnoticed as the players gain the impression of just walking physically through the short tunnel. This concept allows for expanding the users' movements drastically without causing cybersickness through an increased visual flow. However, a perfect shortened tunnel illusion would lead to similar disorientation and lack of impression of the traveled distance known from portals and other relocations. Therefore, our virtual tunnel features window slits that provide a direct peripheral view of the actual expedited movement. Thus, the users gain an impression of moving faster than usual through the windows while the rest of the tunnel serves as a visual rest frame preventing cybersickness effects. The windows' optimal shape and size were fine-tuned in a participatory design phase to account for individual preferences and perceptual differences.

Further, we validate our presented navigation technique against the widely established point & click teleport. Being a completely virtual travel concept featuring instant and free locomotion within the boundaries of the VR game, teleportation can be considered the direct opposite of our approach. Twenty-five participants used both techniques in an immersive game featuring distant points of interest and local tasks. The results of this within-subject study reveal that our presented technique increases physical activity while preventing cybersickness and preserving high levels of presence. Additionally, the experiments show that our concept is easier to learn and use than the teleport technique. In the last part of our paper, we discuss the resulting design considerations and limitations of our proposed locomotion technique.

In sum, the main contributions of our work are the following:

(1) a novel navigation approach for straight paths based on augmented real walking
(2) a within-subject study to compare the performance and reception of our locomotion technique against the teleport
(3) a set of design considerations covering the strengths and limitations of our approach.

2 RELATED WORK

As our work belongs to VR games and locomotion research, we first introduce basic concepts such as immersion, presence, and cybersickness. Next, we cover the current state of research on VR locomotion in general. Finally, we close this section with a deeper look at prior work on augmented movements and portal-based navigation.

VR systems allow users to dive into a virtual, nonexistent world. Thereby, the VR setup's technical ability to suppress the physical surroundings is called *immersion* [7, 15, 73]. If done correctly, the users of such highly immersive systems can experience a feeling of being present in the virtual world [33]. This sensation of *presence* is often a decisive factor in assessing the quality of a VR experience [40, 54, 75]. The work by Slater et al. [76] focuses explicitly on how VR locomotion impacts the perceived presence.

VR applications often suffer from inducing symptoms of cybersickness [35, 49]. Whereas past research has shown that immersive experiences can still be enjoyable despite the occurrence of cybersickness [94], most developers avoid causing discomfort to the users. In the literature, cybersickness is often used interchangeably with the effect of simulator sickness [45]. However, both are different subsets of motion sickness [59, 66]. Simulator sickness [78] is typically caused by technical problems of a misconfigured simulator and leads to mild oculomotor and nausea symptoms [44].

In contrast, the sources of cybersickness lie within a sensory mismatch of the human vestibular and visual systems [69]. The exact reasons remain unclear and are manifested in three theories: sensory conflict theory, poison theory, and postural instability theory [49]. Cybersickness leads to rather severe symptoms [69], such as disorientation and nausea [78]. It is caused by various factors, including technical issues and configurational problems, caused by wrong eye distance or vergence. Also, fast-moving objects combined with a large field of view (FOV) increase the perceived visual flow and contribute to the formation of symptoms [51]. Consequently, limiting the FOV can help in avoiding cybersickness [28, 52]. Finally, Hettinger et al. [34] proposed vection as another causative factor. Vection is a phenomenon where the visual system induces a feeling of self-movement despite the lack of other motion cues. A typical example is watching a nearby train accelerating through the windows of a standing train. In sum, it appears that discrepancies between real movement and observed virtual motion, paired with a high optical flow rate, amplify potential cybersickness.

2.1 Locomotion

Moving through virtual environments is essential for most VR scenarios: exploring extensive worlds, searching for distant points of interest, or traveling to spatially separated locations [56, 86]. Numerous locomotion techniques have been proposed throughout decades of VR research, each with its strengths and weaknesses. As the holy grail of a universal navigation concept may not even exist, locomotion research remains vital to provide fitting approaches for every use case. Considering the vast quantity of existing locomotion techniques, we limit this section to a brief overview. For a detailed summary, we point to existing taxonomies and reviews [3, 8, 9, 50], such as the recent collection *LocomotionVault* [25].

Despite years of research, natural walking is still considered the best locomotion approach [3, 71]. Its intuitive and presence-preserving navigation provide unmatched benefits. Especially when the locomotion task matches the real-world counterpart, real walking is more efficient than virtual travel [83]. Additionally, physical walking helps users construct a cognitive map of the environment [72]. Finally, using the users' real movements for virtual navigation also enable other novel concepts such as using the gait as an input modality [21, 36]. However, the dimensions of the real play area usually limit room-scale tracking to a few square meters.

Therefore, purely virtual navigation techniques decouple the real and virtual movements to achieve an unlimited range of travel. Nevertheless, approaches involving continuous virtual locomotion without a physical counterpart tend to induce cybersickness [32, 77]. A solution is using short and fast movements without acceleration, as these are usually unproblematic [57, 106]. The most prominent approach is the instant teleport [13], which is superior to gamepad locomotion [30]. However, teleportation might break the presence [11] and cause spatial disorientation, as the instant relocations limit the users' ability to estimate the traveled distance [4, 11]. Another popular concept is the world-in-miniature [82], which has been subject to many research efforts. For a review of the extensive design space, we point to the work by Danyluk et al. [23]. Despite numerous proposed concepts, virtual locomotion often fails to achieve the same perceptual qualities as natural walking [91]. Therefore, other approaches aim to preserve the benefits of real walking while overcoming the physical playspace's restrictions. These approaches fall into three categories:

The first group encompasses hardware solutions, such as omnidirectional treadmills [24, 93]. However, these often bulky devices have rarely found their way into broader adoption. Next are concepts that mimic walking through physical mockups, such as walking-in-place [76, 89]. As initial approaches did not feel as natural as real walking [91], later research [27, 87, 105] improved the underlying algorithms, e.g., by involving gait-related biomechanics [96] and switching seamlessly between real walking and walking-in-place [6].

Finally, the last subset comprises hybrid solutions that are based on real walking but extend the available range of movement. Our proposed navigation concept belongs to this category. The most renowned representatives of this subset are redirection techniques, such as redirected walking [67, 68]. They work by unconsciously deviating the virtual locomotion from the real movements. For example, applying slight virtual rotations provokes the users to move in circles while gaining the feeling of walking a straight line. Throughout the last few years, numerous improvements [26, 31, 47] have been proposed, including refining the detection thresholds for different users and conditions [100] or introducing alignment-based redirections that reduce collisions with the physical environment [99]. For an in-depth review of the state of research, we point to the work by Nilsson et al. [64] and Suma et al. [84]. Finally, the *Space Bender* concept by Simeone et al. [74] achieves a comparable effect by overtly altering the environment instead of the users' movements. Nabiyouni and Bowman [62], as well as Cardoso and Perrotta [16], provide more detailed analyses of these and other walking-based locomotion techniques that are not relevant to our work.

2.2 Portals in Virtual Environments

A limited amount of prior research utilized portals for different purposes, such as folding the virtual world [17], without explicitly focussing on their use as a navigation concept. The *Worlds-in-Wedges* concept [63] used volumetric portals to split the surrounding environment, allowing users to view several worlds simultaneously. Finally, portals were also used to transfer between different sceneries [38] or from an entry environment to the target scenario [79, 80].

In locomotion research, portals were mainly employed to redirect users back to the playspace's center and extend the available walking range. In this context, Misztal et al. [58] used portals to prevent cable twists by applying a physical 180° rotation without altering the virtual position or orientation. Freitag et al. [29] also forced users to turn 180°, whereas Liu et al. [53] used a combination of smaller pre- and postportal rotational gains to achieve similar effects. Both works combined the rotational aspect with a positional change to steer the users away from the playspace's boundaries and reduce the frequency of necessary resets. Finally, the *Arch-Explore* [14] technique combined portal navigation with the world-in-miniature concept: users choose a location on a miniature model and then use a static portal to visit the selected site.

Despite the promising applications, these works also reveal the drawbacks of using portals for VR locomotion. Freitag et al. [29] reported that the portal condition performed worst concerning spatial orientation compared to instant teleport and flying. This loss of orientation is also a key gameplay feature behind the game Portal [92]. A possible explanation for the poor comprehensibility of portals might reside in the human ability to form a cognitive map of the direct surroundings. Suma et al. [85] used *impossible spaces*, i.e., virtual scenarios with overlapping geometry, to demonstrate the flexibility of human spatial perception. Most of the time, the participants did not recognize geometrical inconsistencies. The authors speculated that the human mind overlooks most impossibilities as long as the local view stays consistent. This finding might explain the difficulties with portals such as these destroy the users' locally consistent view.

2.3 Augmenting physical movements

Prior work extended the available walking range by amplifying the mapping between the users' real and virtual movements. Applying such translational gains [98], which are mostly used for various redirected walking concepts, remains unnoticed below a detection threshold around $1.25x$ [31, 81]. Within this scope, previous works examined the impact on gait parameters [42] and object selection performance [102]. As larger gain factors also amplify secondary motions, such as head bobbing, the *Seven League Boots* concept by Interrante et al. [41] limited scaling to the intended forward movement during walking. Similarly, Xie et al. [104] also used translational gains combined with resetting. Another approach by Bolte et al. [10] augments the forward movement of a detected jump to travel further.

However, applying translational gains introduces deviations between the virtual and the real movement, which leads to cybersickness [18]. Rietzler et al. [70] combined translational and rotational gains for a perceivable redirection approach but reported significantly more cybersickness symptoms than with teleportation. Similar effects on sickness levels were also reported for large translational gains, where almost 50% of subjects reported considerable symptoms [88]. Apart from the experienced cybersickness, prior research also emphasized adverse effects on accuracy and the need for a clear distinction of local and accelerated walking [101]. Finally, Abtahi et al. [2] also suggested an increased acclimation time, as users may only experience the applied speed gain after beginning walking. Instead of putting up with these drawbacks of translational gains, one might scale the complete player by increasing the height and eye distance accordingly [20, 46]. This concept preserves the proportions between real and virtual movements. Instead of causing cybersickness, it leads to the impression of walking through a toy world and allows for comfortable accelerated locomotion.

3 TUNNEL-BASED LOCOMOTION CONCEPT

Our proposed navigation technique extends the walking range without causing cybersickness by combining two concepts: We apply a translational gain in the target direction and use a virtual portal to create a space-bending illusion. Similar to the *Seven League Boots* technique [41], our concept increases the users' movement in the forward direction. However, we do not infer the intended walking direction but only augment the movement in the direct line between start and target. Consequently, our navigation technique focuses on fixed and straight routes between a predetermined start point p_s and an endpoint p_e. This design decision prevents the loss in accuracy that is typically observed with scaled movements. As users travel between the start and endpoint, they cover the virtual distance $d(p_s, p_e)$. However, in reality, augmenting the movement speed by a transitional gain factor a_g reduces the walking distance to $d(p_s, p_e)/a_g$. For example, traveling $60m$ from one point of interest to another requires $2m$ in the actual play space with a gain factor of $30x$.

Previous research showed that although this kind of translational movement effectively enhances the movement range of real walking, it may also cause cybersickness. Therefore, we constructed a virtual tunnel to increase the available walking range through translational gains while avoiding adverse side effects and preserving the advantages of natural walking to physical activity and spatial orientation (see Figure 2). This virtual tunnel consists of an exterior component, the *hull*, and an interior element, the *cabin*. The tunnel's hull is mainly used to illustrate the actual travel distance before the users enter the tunnel. The hull features an entry and exit arch and exterior tunnel walls and roof that span the entire distance $d(p_s, p_e)$. Therefore, the users may investigate the tunnel from the outside and understand that it spans from their position p_s to their target p_e. The tunnel's cabin is an enclosed room fitting into the tunnel's hull. The cabin's length is $d(p_s, p_e)/a_g$, as this is the actual physical distance for the users to walk. Whereas the walls to both sides, the floor, and the roof consist of solid surfaces, the two sides covering the cabin's entrance and exit are portals displaying the actual tunnel's ends. This construction provides the impression of a shortened passage within the actual long tunnel. To the players, the two parts hull and cabin merge into one tunnel, which appears to be very long on the outside, but relatively short when looking through it.

When the users enter the tunnel, the rig, determining their position in the world, is made a child object of the cabin. As the users walk through the passage, the cabin is moved accordingly with

Fig. 2. The virtual tunnel, as the core of our novel locomotion technique: The exterior *hull* spans from the start point to the target. While users walk through the *cabin*, it is moved along the tunnel to transport the users to their destination. The cabin's walls and portals create an optical illusion, whereas the windows provide a view of the accelerated movement. Users initiate the tunnel by standing on a platform and pressing a button.

an increased speed of $v * a_g$. As a result, the cabin reaches the tunnel's far end just as the players arrive at the cabin's exit portal. This concept is similar to an elevator moving within its shaft. As the portal conforms with the actual view, the users do not notice a visual difference when leaving the cabin. This construction provides the perfect impression of walking through a short tunnel and exiting at the rear side, arriving at the distant target. The players are shielded from the increased optical flow arising from the augmented movement, so we do not expect any cybersickness.

However, the tunnel hides the actual long-distance travel in this form and would probably diminish the players' spatial orientation and feeling of traveled distance. Therefore, we deliberately break this perfect illusion by adding windows to the cabin's sides. These expose the actual virtual locomotion speed. By doing so, we aim to provide a better impression of the travel experience. Still, we assume that the rest of the cabin, i.e., the portals and the walls, suffice to provide a steady reference point reflecting the actual walking speed and preventing cybersickness. Related concepts in prior research are dynamic FOV limiters that shield users from increased visual flow [28, 52]. However, such techniques overtly reduce the players' view of the virtual environment and could diminish the player experience. In contrast, our approach uses diegetic and thematically embedded geometry to achieve a similar effect while preserving a partial view of the occluded areas through the windows. Thereby, we aim to reduce any potential disturbance to a minimum.

Of course, determining the best shape and size of the windows is essential. Both extreme cases do not provide the wanted effects: tiny windows fail to raise an impression of fast movements, whereas huge windows, covering the complete walls, increase the visual flow and potentially induce cybersickness. Therefore, we evaluated different window sizes and shapes in a participatory design phase with four participants with a mean age of 40 (SD = 17.62). Despite the limited subject count due to COVID-19 restrictions, we made sure to include different degrees of VR expertise and susceptibility to cybersickness. All tested designs featured the same solid wall material and an almost transparent glass surface serving as a window to the outside environment. Although traditional rectangular cutouts provided the best impression of the travel experience, extended use sometimes induced mild symptoms of vection-based cybersickness. We assume that the missing visual reference frame when the windows fill the users' view might have caused this experience. For this reason, a design consisting of horizontal window stripes was favored by most participants.

Additionally, the resulting effective window size is larger than traditional windows but split into small stripes, providing an optimal steady reference.

Finally, we aimed to increase the impression of traveling a longer distance by adding decorative and animated elements. Therefore, we used arrows with switching colors on the cabin's floor to provide a similar effect as the acceleration fields in many games, such a Mario Kart [65]. Also, we added animations when the tunnel appears and disappears. After enabling the tunnel, the users see it rising to half its height from the floor. Then, the tunnel expands in length until it reaches the target destination before rising to full height. Finally, the tunnel's doors are opened and allow the users to traverse it. After the users arrive at their destination, the doors close automatically, and the tunnel is retracted into the ground. Whereas our concept would still work without these effects, we presume that they further strengthen the players' impression of the actual travel distance. Also, the brief pause induced by the animations helps distinguish the local navigation and the long-distance travel.

In sum, our virtual tunnel is a novel locomotion technique focussing on straight and predetermined paths. It aims to prevent the adverse side effects of large translational gains by hiding most of the visual flow and providing a steady reference frame while providing a restricted impression of the movement through fixed windows.

4 EVALUATION

We conducted a lab study to evaluate our proposed navigation concept. Therefore, we used an urban virtual environment to compare the augmented-walking approach against the commonly used *point and teleport* technique [13]. We were interested in the qualitative and quantitative differences in the efficacy of both methods, especially regarding usability, spatial orientation, and cybersickness.

4.1 Research Questions and Hypotheses

Our primary research goal is to explore the differences between our introduced augmented-walking technique and instant teleportation. Apart from being probably the most commonly used locomotion technique in recent games and applications, we mainly chose the teleport for its completely contrastive properties. Whereas our approach limits navigation between points of interest to a fixed and straight route, teleportation enables players to navigate the world freely within the boundaries of the reachable game world. This traveling happens instantaneously compared to our concept, which is based on real walking and involves short animations. Finally, the teleport is well-known for the shallow learning curve and the absence of cybersickness. Altogether, the different characteristics promise intriguing insights into the individual strengths and weaknesses. Therefore, we compare both approaches regarding the eight performance metrics proposed by Bowman et al. [12] to assess the efficacy of locomotion techniques: speed, accuracy, spatial awareness, ease of learning, ease of use, information gathering, presence, and user comfort.

4.1.1 User Comfort. The primary motivation of our work is to avoid the possible cybersickness typically observed with disparities between real and virtual velocity. Our tunnel shields the user from most of the increased visual flow, so we assume that it effectively prevents cybersickness.

4.1.2 Speed and Accuracy. In contrast to the user's comfort, a high travel speed is not a crucial requirement for VR locomotion techniques. Instead, it should suit the intended use case and allow users to move through the virtual environment without causing boredom or fatigue. As our navigation concept is based on real walking, we expect to observe significantly longer travel times compared to instant teleportation. At the same time, we suppose that users walk further and feel more physically active.

Due to the conceptual differences between both locomotion techniques, we do not compare the navigational accuracy. In contrast to the teleport, users must choose their final destination for the virtual tunnel directly at the start. Precisely setting a navigation target at a distance of more than 50 meters is not doable with the visual pointer used for teleportation. A possible solution would be to use a dedicated interface, such as a minimap or WIM, to determine the target. However, this design decision introduces an additional interaction concept, which might bias the evaluation. Therefore, we exclude this step from our study and instead employ tunnels with fixed start and end positions. The users initiate the tunnel by standing on a small platform and pressing a knob in the virtual scenario, similar to an elevator button. This design decision has implications for the user experience, as discussed later in the paper.

4.1.3 Spatial Awareness and Information Gathering. Real walking positively impacts the human ability to generate a cognitive map of the surroundings and thus leads to improved spatial awareness and a better impression of the environment. Whereas these findings suggest a positive effect of our augmented-walking technique, the surrounding tunnel hides part of the scenery during the travel and might reduce the benefit. Still, we assume that the windows provide a good view of the scene and significantly benefit spatial orientation compared to immediate teleportations.

4.1.4 Ease of Learning and Ease of Use. Apart from providing an effective, comprehensive, and comfortable travel experience, locomotion techniques must also be easy to learn and use. Our navigation approach merely requires the user to open the tunnel and walk through it. Both are activities we perform every day, e.g., when using an elevator. Therefore, we assume that the tunnel is reasonably easy to master. However, the teleport is also known for simplicity and is the preferred choice in action-intensive VR games. Thus, it remains an open research question how these two techniques compare regarding usability and mastery.

4.1.5 Presence. Finally, the success of immersive VR experiences largely depends on the users' perceived feeling of presence. This sensation is influenced by most aspects of the VR application, including the utilized locomotion technique. Even though real walking is commonly believed to be the most natural movement concept, past research has revealed mixed results concerning the effects on perceived presence. Whereas some walking-based approaches elicited higher presence levels [20, 46, 91], other comparing studies could not confirm such effects [48]. The lacking consensus prevents us from hypothesizing potential significant effects. Instead, we pose a research question to investigate the influence of the two conditions on presence.

To summarize, our hypotheses and research questions are:

- H1: The presented augmented-walking approach does not induce cybersickness.
- H2: Compared to teleportation, our locomotion technique significantly increases the walked distance and the overall travel time.
- H3: The introduced tunnel concept significantly benefits spatial orientation and gives a better impression of the traveled route compared to teleportation.
- RQ1: How does our locomotion technique compare to teleportation regarding mastery and ease of control?
- RQ2: Do both navigation approaches differ concerning perceived presence?

4.2 Testbed Scenario

We realized our testbed game to compare both navigation techniques using the Unity game engine 2021.2.0b4 [90]. Our virtual environment is a futuristic city featuring narrow alleys, wider streets, and ample open spaces (see Figure 3). The style is similar to dystopian cyberpunk scenarios to allow for easy integration of the required mechanisms. The subjects can move only within the

Fig. 3. Overview of the testbed environment, including the two levels $L1$ and $L2$, the *energy supply* task (A), the *garbage collection* task (B), the distance estimation (C), and the instruction drone (D).

designated play area throughout the study, consisting of seven points of interest, connected by six direct paths. The scene's geometry, i.e., buildings, vehicles, fences, or barriers, is designed to form a single path without requiring explicit boundaries.

As we aimed for a within-subject design, we designed two nearly identical levels $L1$ and $L2$. Both encompass different streets in the same testbed scenario and share most properties, such as the distance and angle between the points of interest. We exchanged only the visuals, such as the surrounding buildings, to avoid repetition effects. Additionally, we created two similar local tasks for the points of interest. Both rely on the same principle: sorting colored items into matching slots. In the first task, *energy supply*, the users take three energy cells from a central point of issuance and place them into the correct loading facilities. In the second task, *garbage collection*, the users collect three garbage bags and place them into one of the three garbage bins. No additional locomotion technique is required for the tunnel condition, as designing the environment with the lab dimensions in mind ensures that all interactables are reachable by real walking within the boundaries of the play area. Our task design combines the investigated long-range navigation with local interactions and thus resembles typical game plots. Also, it ensures good comparability as both tasks use the same principle and employ a similar walking pattern.

Each level is structured identically: The subjects begin the experience at the starting location of the respective level $L1$ or $L2$. A nonhumanoid drone provides the necessary instructions for completing the assigned task. Depending on the level, the users must complete either the energy supply or garbage collection task. Then, they are introduced to the locomotion technique, i.e., augmented walking or teleport, and use it to travel to the second point of interest. After arriving there, the subjects estimate their traveled distance. The resulting estimation errors are later analyzed for differences between the conditions. Thereby, the six paths between the seven checkpoints have three different lengths repeating twice: $60m$, $75m$, $45m$, $75m$, $45m$, and $60m$. As we applied a constant gain factor of $30x$, this design leads to tunnel lengths between $1.5m$ and $2.5m$. After entering their distance guess into a terminal, the users continue the pattern — task, travel, distance estimation — until the last task at the final checkpoint is completed. Finally, the drone reappears and debriefs the subjects.

4.3 Procedures and Applied Measures

We conducted a within-subject study and applied a cross-over design to avoid sequence effects, i.e., subjects either started with teleport or augmented walking. Additionally, we wanted to avoid repetition effects through learning the local task. Therefore, we counterbalanced the order of tasks. That said, each subject started with a combination of one task and one locomotion technique and replayed the opposite combination in the second round. The study took 45 minutes on average and was conducted in our $16m^2$ lab using an HTC Vive Pro [37].

In the beginning, we informed the subjects about the overall procedure and the general study's goals. Before the first round, we assessed the subjects' general information, such as gender, age, and prior VR and gaming experience. Next, we introduced the subjets to the VR setup, assisted them in adjusting the headset properly, and explained the functionality of collision warnings. After these preliminary steps, we started the first level, where the subjects received their instructions. Throughout the playthrough, we logged the relevant statistics needed for our hypotheses H2 and H3: walking distance, travel duration, and the subjects' personal distance estimations. For the travel duration, we measured the time from completing all tasks at one checkpoint until reaching the next checkpoint. Therefore, these timings also include the necessary time to invoke the tunnel. After completing the level, the subjects completed a set of questionnaires assessing their personal experience.

First, we administered the Simulator Sickness Questionnaire (SSQ) [43] to test our hypothesis H1 and examine possible cybersickness effects. The SSQ consists of the three subscales nausea, oculomotor, and disorientation, using a range from 0 (none) to 3 (severe) for the individual elements. As we were interested in the influence of the locomotion technique on the perceived presence (see RQ2), we used the Presence Questionnaire (PQ) (initially developed by Witmer and Singer [103] and later revised by the UQO Cyberpsychology Lab [22]). It allows for a closer look at the locomotion-related influences on presence and includes five subscales: realism, possibility to act, quality of interface, possibility to examine, and self-evaluation of performance (coded 0 - 6). For RQ1, exploring the usability of the navigation concepts, we assessed three subdimensions of the player experience inventory (PXI) [1]: ease of control, autonomy, and master (all coded -3 - 3). Finally, the questionnaires were complemented by eight custom questions (coded 0 - 6). These covered spatial orientation, a key concern in H3, and other locomotion-related questions, expanding our understanding of the different locomotion techniques. Semistructured interviews finished the study to allow all subjects to share their experiences.

5 RESULTS

Based on the circumstances during data collection, i.e., the COVID-19 pandemic, prior experiences from other studies, and a preliminary power analysis, we aimed for a sample size of N=25. As the significance threshold, we chose $\alpha = .05$. These factors enable the detection of effect strengths of $d = 0.6$ with 80% power. For our study, we applied strict hygiene measures to ensure the safety of our participants. These measures included the mandatory use of face masks, regular airings, and disinfection of the headset after every use. The 25 recruited participants (10 female, 15 male) with a mean age of 27.84 (SD=13.92) reported playing digital games at least a few times per month (80%) and mainly had used VR systems before (92%). Only a minority stated they were using VR on a regular basis (24%).

Our study comprised two locomotion techniques, which are subsequently referred to as tunnel and teleport. Also, we used a pair of similar local tasks in two levels with equal geometrical layouts. Thus, we split the subjects randomly into four groups. Each started one locomotion technique and one task and played the opposite combination in the second round. This cross-over design accounts

Table 1. Mean scores, standard deviations, and paired sample t-test values of the Presence Questionnaire (PQ), the Player Experience Inventory (PXI), and the Simulator Sickness Questionnaire (SSQ).

	Tunnel M(SD)	Teleport M(SD)	$t(24)$	p		d	CI
PQ (scale: 0 - 6)							
Realism	4.18 (0.89)	3.76 (0.92)	2.526	.019	*	.505	[.076, .758]
Possibility to Act	4.27 (0.91)	4.33 (0.93)	-.417	.680		-.083	[−.357, .237]
Interface Quality	4.97 (0.76)	4.93 (0.80)	.323	.749		.065	[−.215, .295]
Possibility to Examine	4.48 (0.98)	4.31 (0.85)	1.192	.245		.238	[−.127, .474]
Performance	4.94 (0.79)	4.60 (0.91)	1.846	.077		.369	[−.040, .720]
Total	4.45 (0.71)	4.23 (0.71)	2.241	.035	*	.448	[.017, .404]
PXI (scale: -3 – 3)							
Mastery	1.56 (1.04)	1.52 (0.98)	.285	.778		.057	[−.250, .330]
Autonomy	-0.33 (1.71)	-0.60 (1.36)	.900	.377		.180	[−.345, .878]
Ease of Control	2.37 (0.75)	2.09 (0.78)	2.929	.007	**	.586	[.083, .477]
SSQ (scale: 0 - 3)							
Nausea	13.74 (15.35)	12.59 (17.57)	.768	.450		.154	[−1.931, 4.220]
Oculomotor	17.28 (17.16)	16.98 (16.70)	.157	.877		.031	[−3.683, 4.290]
Disorientation	25.06 (38.75)	19.49 (31.64)	1.477	.153		.295	[−2.212, 13.348]
Total	20.64 (23.06)	18.55 (21.31)	1.028	.314		.206	[−2.112, 6.301]

$^{*}p < .05$, $^{**}p < .01$

for potential sequence and learning effects. To confirm comparability between both local tasks, we grouped trials sharing the same locomotion technique and compared the time subjects took to complete the local assignments at every checkpoint. This average task completion time differs significantly for neither the teleport condition ($task_{energy} = 72.09$ (SD=18.65); $task_{garbage} = 65.06$ (SD=19.74); $t(23) = .912$; $p = .371$; 95% $CI[-8.90, 22.95]$) nor the tunnel condition ($task_{energy} = 51.35$ (SD=14.98); $task_{garbage} = 57.15$ (SD=12.85); $t(23) = -1.034$; $p = .312$; 95% $CI[-17.39, 5.8]$). Even though means differ by 10%, we attribute this result to chance, as the sign differs between both locomotion techniques. This observation speaks against a structural difference between both tasks. Thus, we treat both tasks as equivalent for further analysis.

Consequently, we compared only the evaluated measures between both within-conditions tunnel and teleport with paired sample t-tests. Beforehand, we ensured the test's assumptions by testing for normal distribution with Shapiro-Wilk tests. All listed calculations were executed with IBM SPSS 27 [39]. In the following section, we report the significant differences between conditions, including all necessary information, such as the effect strength and the confidence interval, to ensure reproducibility [95].

5.1 Questionnaires

In order to confirm our hypothesis H1, we assessed the SSQ. The resulting weighted scores are shown in Table 1. They indicate no noteworthy cybersickness symptoms according to reference values by Kennedy et al. [43] Besides, both conditions do not differ significantly, and the small confidence intervals of the means suspend the presence of a larger undiscovered effect. Furthermore, we measured the perceived presence between both conditions to answer RQ2. Whereas most subscales of the PQ (see Table 1) are almost equal for the teleport and our approach, the paired sample t-tests for the total presence score and the realism subscale indicate an observed medium effect according

Table 2. Mean scores, standard deviations, and paired sample t-test values of the custom questions (CQ).

Question Item	Tunnel M(SD)	Teleport M(SD)	$t(24)$	p		d	CI
CQ1 I could orient myself well in the virtual world.	4.12 (1.51)	4.68 (0.95)	-2.064	.050		-.413	$[-1.120, .000]$
CQ2 After each relocation, I needed a moment to orient myself.	3.12 (1.81)	2.56 (1.85)	1.184	.248		.237	$[-.416, 1.536]$
CQ3 I gained a good impression of the traveled distance.	2.96 (1.62)	3.12 (1.39)	-.458	.651		-.092	$[-.882, .562]$
CQ4 I felt very active while playing.	4.08 (1.41)	3.32 (1.57)	2.282	.032	*	.456	$[.073, 1.447]$
CQ5 I think I have been walking much in the real room while playing.	4.48 (1.45)	3.28 (1.54)	2.969	.007	**	.594	$[.366, 2.034]$
CQ6 Traveling longer distances was cumbersome.	0.60 (0.87)	1.36 (1.29)	-2.317	.029	*	-.463	$[-1.437, -.083]$
CQ7 I would have preferred to move through the world using another technique.	2.24 (1.64)	2.56 (1.56)	-.858	.399		-.172	$[-1.089, .450]$
CQ8 I was able to control the navigation between the different locations.	1.96 (1.54)	4.12 (1.39)	-5.014	.000	**	-1.003	$[-3.049, -1.271]$

$^{*}p < .05$, $^{**}\ p < .01$

to Cohen's d. However, as the confidence intervals include both trivial and meaningful differences, we cannot reach a decisive conclusion concerning the effect's nature. Finally, we assessed the PXI subscales mastery, autonomy, and ease of control. Only the statistically significant differences for ease of control suggest the presence of a medium effect.

5.2 Custom Questions

Besides the aforementioned standardized questionnaires, we also administered eight custom questions to confirm our hypothesis H3 and gain further insights into the personal user experience. These questions were split into three parts: The first three questions covered spatial orientation. Next, we included three questions on physical activity and closed with two general questions on personal preference and autonomy. The results for all questions are shown in Table 2. The items concerning orientation are not statistically significant. In contrast, all three questions covering the feeling of activity imply the presence of medium effects. It appears that subjects felt more active when using the tunnel approach without experiencing it as cumbersome. Finally, the last question reveals that the subjects felt far less autonomous when using our presented concept.

5.3 Logging Data and Distance Estimations

For H2, we assumed that our augmented-walking approach provokes the subjects to walk more while traveling longer. To confirm this hypothesis, we logged the necessary data throughout both rounds (see Figure 4). Whereas the average total travel time between checkpoints for the tunnel condition was 9.33% higher, this difference was not statistically significant ($t(24) = 1.236$; $p = .228$;

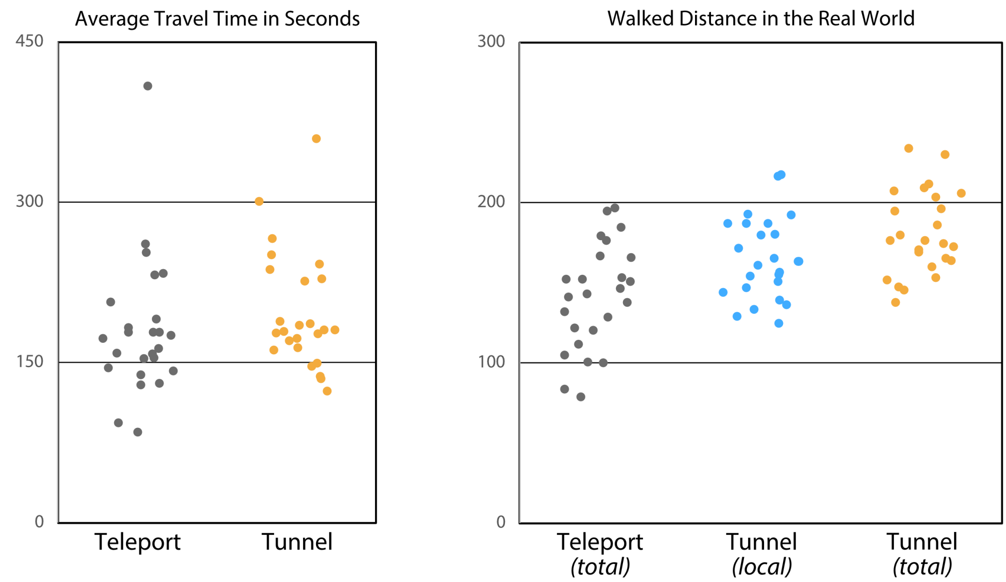

Fig. 4. Results from the data logged during the study. Left: the difference in travel time for both conditions in seconds. Right: the average distance (in meters) subjects walked in the real room. For the tunnel condition, *local* indicates the distance subjects walked at the local checkpoints. In contrast, *total* measures the sum of local navigation and the distance subjects walked through the tunnels. For the teleport condition, only the walked distance in *total* is provided.

d = .247; 95% $CI[-11.255, 44.865]$). However, subjects using the tunnel concept walked 28.37% more compared to the teleport condition. This difference is highly significant and implies a very large effect ($t(24) = 6.292$; $p < .001$; $d = 1.258$; 95% $CI[26.850, 53.065]$). Even after subtracting the necessary walking distance through the tunnels, the difference in the remaining local walking distance remains significant ($t(24) = 3.916$; $p < .001$; $d = .783$; 95% $CI[11.584, 37.396]$). This finding reveals that subjects also tended to rely on teleportation overly and thus walked 14.81% less while completing the local tasks.

Finally, the subjects also had to estimate their traveled distance from one checkpoint to another. We aggregated these individual estimations by calculating the mean squared error (MSE) compared to the correct distance. In this step, we had to exclude three extreme outliers with MSEs above 1300. The remaining data suggest that the teleport technique leads to slightly better distance estimations: $MSE_{teleport}$ = 322.64 (SD=204.49), MSE_{tunnel} = 406.75 (SD=245.89). However, this difference is not statistically significant ($t(21) = -1.641$; $p = .116$; $d = -.350$; 95% $CI[-190.735, 22.508]$). Examing the unsquared errors (ME) reveals that the subjects generally underestimated the distance: $ME_{teleport} = -2.45$ (SD=13.56), $ME_{tunnel} = -6.14$ (SD=13.52).

6 DISCUSSION

In general, all subjects enjoyed participating in our study and could complete all tasks without difficulties. Whereas most subjects were familiar with the teleport concept, none had previously used an accelerated walking approach. Nevertheless, multiple subjects reported past experiences with cybersickness when using artificial navigation concepts, such as gamepad locomotion. As such symptoms cause unwellness that can retain for hours, some subjects were extra cautious when trying VR applications. Consequently, the avoidance of cybersickness was our main priority, followed by two further hypotheses and research questions covering the relevant qualities of locomotion techniques.

H1: The presented augmented-walking approach does not induce cybersickness.

According to the results of the SSQ, our locomotion technique did not cause cybersickness symptoms. Moreover, the observed values are equal to the ones of the teleport condition. This finding is promising as teleportation is usually also chosen for its superior tolerability for sensitive users. Furthermore, we did not observe any adverse effects despite applying a large gain factor to the virtual movement, which induces high visual flows and causes cybersickness. This finding is to be emphasized as prior research reported the occurrence of cybersickness symptoms already at gain factors below $10x$ [88]. In sum, these results confirm our primary hypothesis H1.

Despite these promising results, there was a single case of mild symptoms of dizziness after using the tunnel technique. Our subsequent interview suggests that the observed indications might result from the subject testing the limitations of our navigation concept. For instance, the respective subject repeatedly leaned forward and back in the tunnel's center while looking through the windows. Even though this behavior was not intended, we emphasize the need for further investigation. A possible solution to this drawback might be to use center-of-mass displacement instead of head displacement for the movement scaling. Finally, we only assessed the SSQ after the study condition and not additionally in advance. Whereas this study design is used in a variety of prior studies [29, 46, 49], it might have introduced a confounding factor, as we cannot account for the pre-study state of the subjects.

H2: Compared to teleportation, our locomotion technique significantly increases the walked distance and the overall travel time.

For the tunnel condition, we used our presented walking-based travel approach paired with real walking for the local tasks. This combination increased the total walked distance significantly. What is more, it also permitted us to avoid using virtual locomotion techniques in this condition. As a consequence, the subjects also walked significantly more while completing the local tasks. In contrast to this outcome, the teleport concept encouraged the subjects to rely on teleportation exclusively, regardless of whether a target was reachable by real walking or not. This finding was already reported in other papers [20, 29, 46] and is also reflected in the custom questions as the subjects felt more active in the tunnel condition.

We also assumed that the observed extended walking would increase the total travel time compared to the instant teleport. However, we could not confirm this part of the hypothesis. Instead, both concepts required a similar time to travel between the checkpoints. It seems that the tunnel locomotion, i.e., waiting for the tunnel animation before walking $1.5m - 2.5m$, does not take longer than aiming and teleporting multiple times.

H3: The introduced tunnel concept significantly benefits spatial orientation and gives a better impression of the traveled route compared to teleportation.

We assessed the difference in spatial orientation and overview using three custom questions and the distance estimations. However, these measures could not confirm our hypothesis. Instead, the means of the questions and MSEs point slightly towards the teleport for providing better orientation. Nevertheless, this difference is not significant. We assume that the reasons for this equality mainly reside in the tunnel's geometry. Although being necessary to prevent cybersickness, the tunnel's walls hide most of the surroundings during travel. We added the windows to diminish the adverse effect of the partial occlusion. However, they might not have sufficed to deliver the benefits of real walking. Still, the performance of our novel locomotion concept is comparable to the teleport, which is one of the most commonly used techniques. In future research, we plan to investigate this topic further by finetuning the window slits for an optimal view and conducting a study with a dedicated orientational task.

RQ1: How does our locomotion technique compare to teleportation regarding mastery and ease of control?

We did not formulate a confirmatory hypothesis for the locomotion technique's usability, since we compare our approach against teleport, which is known for its simplicity and easy usage [13]. Still, the tunnel concept does not require prior training by relying solely on real walking. To investigate how both techniques compare, we assessed three PXI subscales and two custom questions. Both techniques were rated equally popular (CQ7) and easy to master. However, the tunnel concept appears to be slightly easier to control than the teleport. This significant result of the PXI reflects verbal feedback of multiple subjects, one of whom stated, *"it took time to get used to the two controller buttons for object manipulation and teleporting"(**P10**)*. At the start of the teleport condition, few subjects confounded the inputs and accidentally teleported themselves. Thus, the tunnel might be easier for beginners by employing known concepts.

RQ2: Do both navigation approaches differ concerning perceived presence?

Finally, we were interested in how the locomotion techniques influence the perceived presence. In general, most PQ subscales are almost identical. The two notable differences are the realism subscale and the total presence, which are both significantly higher for the tunnel condition. Of course, the presence sensation is very individual and highly scenario-dependant. However, some subjects stated that *"the teleport felt a bit too unrealistic by happening instantaneously"(**P16**)*. The tunnel had no such visual cut and felt smoother in movement.

7 DESIGN CONSIDERATIONS AND LIMITATIONS

Our proposed navigation concept extends on existing augmented-walking approaches and effectively prevents cybersickness by hiding the increased visual flow. Thereby, it adds to the growing collection of existing locomotion techniques for virtual environments. In this section, we discuss the decisive design considerations and limitations concerning the application of our approach for VR experiences.

Benefits of a Walking-based Locomotion Technique. As explained earlier, using real walking for VR locomotion causes the users to feel more active [21] and potentially boosts spatial orientation [72]. Two additional benefits were mentioned by our study subjects. Multiple subjects reported an increased feeling of safety while using the tunnel concept. When using teleportation, *"one would often end up in one corner of the real room, without enough space to interact with the environment"(**P4**)*. In contrast, the tunnel condition used the real playspace effectively so that *"one could use all tunnels and solve every task without even seeing the collision warning once"(**P1**)*. This benefit is achieved in this particular case by designing the virtual environment with the real surroundings in mind, which requires knowledge of the playspace in advance and is also impossible for free teleport locomotion. Finally, one subject stated another simple reason for preferring the walking-based concept: *"Without the teleport, I could use both hands at once and carry two items at the same time"(**P2**)*.

Choosing the Gain Factor. For our study, we selected a fixed translational gain factor of $30x$. This decision was based on the size of the virtual world and the available tracking space. Thus, other applications likely require different gain factors to use our locomotion technique effectively. Even though we cannot generalize our results to the performance of other translational gains, our concept still avoids most of the issues observed in previous research with values lower than $10x$. In general, two approaches for realizing different gains are feasible: In our case, we preselected a fixed gain factor, which produced tunnels of various lengths, ranging from $1.5m$ ($45m$ virtual distance) to $2.5m$ ($75m$). Alternatively, one could use a standardized tunnel distance, such as $2m$, and vary the gain factor based on the virtual path. The final option is to adapt the gain factor according to the remaining physical space in front of the user to use the playspace more effectively. Extending this approach to curved tunnels could be used to steer players away from the walls and thereby minimize potential resets. Regardless of this design decision, future work is still needed to identify possible lower and upper bounds to the gain factor concerning cybersickness and travel experience.

Setting the Navigation Target. Opposing the point and teleport concept, our locomotion technique works along a straight path from the users' current position to a predefined destination. However, this design requires setting the target position before deploying the tunnel. In our study, we used the tubular level design to set fixed navigation goals between the checkpoints. This design decision limits the players' freedom to navigate freely, which is clearly reflected in the results of CQ8. However, this experience did not negatively prejudice the overall game experience, as seen in the equal scores of the PXI's autonomy subscale. Past research emphasized that the primary use case of large translational gains mainly resides within "large displacements along non-relevant areas" [60]. Many games employ a similar environmental design of distinct points of interest and neglectable transitional areas, and we argue that our concept is particularly suited for such scenarios. However, freely explorable environments require additional user interaction to set the next locomotion target. Visual pointers, used for various navigation techniques, perform poorly for long distances due to the so-called "fishing-rod problem". Instead, dedicated visualizations, such as minimaps or worlds-in-miniature, provide a better solution, preserving accuracy regardless of the travel distance. These concepts are also compatible with fixed navigation anchors to combine self-determined locomotion with the benefits of a pre-planned walking experience.

Restrictions on the Virtual Environment. By design, our augmented-walking concept does not require strict design characteristics with respect to the surrounding virtual world. It works well in a variety of environments, ranging from broad and open scenarios to narrow indoor areas. The only decisive prerequisite is the straight, occlusion-free path between start and end position. In future work, we aim to investigate a possible extension to curved routes. In this case, the tunnel's cabin would remain rectangular but follow the path's course during locomotion. Also, we did not investigate whether the direct surrounding influences the users' travel experience. Narrow paths might provide a poorer impression of the surroundings than broad areas. Although we eliminated this factor in our study by using similar level geometry, future exploration of possible influences is decisive for broader application.

Restrictions on the Playspace. Apart from limitations to the surrounding virtual scenario, our tunnel concept requires at least a medium-sized play area. Generally speaking, larger spaces allow for longer tunnels without reaching the physical boundaries at every tunnel entry and exit. The necessity to entirely leave the tunnel before it disappears significantly reduces the maximal tunnel length compared to the available space. For instance, for our $16m^2$ lab, we decided on a maximal tunnel length of $2.5m$ to avoid complicated maneuvering in the playspace's corners. To a certain degree, short tunnels can be compensated for by increasing the gain factor further. However, this design decision risks diminishing the players' impression of the virtual travel and should be used with caution. In the end, the usability and effectiveness of the tunnel technique depend on the ratio between virtual and real travel distances. Consequently, we recommend this locomotion technique only for medium to large playspaces, starting at about $16m^2$.

Windows. Apart from preventing cybersickness, our novel tunnel concept also aimed to provide an optimal travel experience through windows in the tunnel's walls. Our chosen design — horizontal stripes — was carefully chosen in a participatory design phase to combine a good view with a steady visual anchor point. Whereas the concept generally worked well, the spatial orientation was similar to the teleport condition and not superior as expected. One potential reason might reside in the age difference between the participants of our participatory design phase and the subjects of our study. As we optimized the size and shape of the window slits according to the feedback of our early testers, these properties might not have been optimal for the larger player base in the main study. Additionally, we only measured differences in spatial cognition through questionnaires. For an advanced understanding of the underlying effects, alternative measurements are preferable, such as pointing tasks or map-drawing tasks. Therefore, future research should approach these shortcomings to determine the optimal window size that combines cybersickness-free augmented walking with optimal spatial knowledge.

Embedding and Animations. We used a thematic style and transitional animations for our implementation and user study. These optional design elements are primarily cosmetic and have a minimal effect on the actual locomotion experience. Nevertheless, they offer valuable advantages. Firstly, Marwecki et al. [55] argue that techniques, such as the Seven-League Boots concept, involve an overt deviation between physical movements and virtual locomotion, which could reduce "the immersive quality of real walking". In contrast, our movement acceleration occurs within the tunnel's static geometry and ends when reaching the exit. This diegetic embedding transforms the dedicated locomotion technique into a feature of the virtual environment, leaving the original one-to-one mapping of real walking intact.

Furthermore, previous augmented walking concepts were only experienceable after the users began walking and could easily lead to confusion. Instead, our tunnel's geometry and the animated doors emphasize a clear cut between the locomotion modes. However, invoking the tunnel and waiting for the intro animation pose a considerable interaction overhead. In our study, no participant was bothered by this design, and both locomotion techniques also performed similarly despite this overhead. Nevertheless, repeated use of our technique in longer play sessions might annoy players. Thus, we propose adapting the animation speed in subsequent invocations after an initial adaptation phase.

8 CONCLUSION

Tracking the users' movements in the real playspace and translating them into the virtual world is widely considered the gold standard for VR locomotion. However, the physical constraints of the available tracking space usually limit the applicability of physical walking for larger environments. One possible solution is to scale these movements and thereby enable users to walk further in VR. However, such augmented virtual motions increase the visual flow and are known to induce cybersickness. Also, established concepts often suffer from poor accuracy and implementation hurdles. Our presented technique is a novel alternative that uses a tunnel concept to shield the players from excessive visual flow. While the players walk through this seemingly short tunnel, they perceive only their accelerated forward motion through windows in the tunnel's walls.

In contrast to the well-known teleport technique, our approach increases the perceived and actual physical activity while effectively preventing cybersickness and preserving high levels of presence. Also, our within-subject study revealed that the concept is more beginner-friendly than the teleport approach. In the last part of the paper, we summarized the resulting design considerations and the limitations of our technique. Our future research will focus on the various open questions and possible improvements explained in the previous section, including a closer investigation of different gain factors and window shapes and the exploration of curved paths and self-set navigation targets.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	**Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion** *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put…": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion

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Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion

Under Review, Submitted to CHI'23

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ABSTRACT

In principle, virtual reality allows users to immerse themselves in virtual worlds of all sorts and sizes. However, the size of such environments often exceeds the available physical tracking area. Minimal stationary setups are especially problematic as they do not meet the requirements for most locomotion techniques, such as real or accelerated walking. Consequently, developers often use virtual navigation concepts that work with every setup but fail to convey the same degree of naturalness and realism. On the other hand, gesture-based approaches, such as walking-in-place or arm-swinging, often provoke unintentional real movements or suffer from poor precision. Therefore, we present a novel locomotion technique that combines point-tugging and arm-swinging. Depending on the desired movement, users dynamically switch between two modes. Raising the arms in front of the chest enables precise point-tugging for local navigation. Swinging the arms at waist level is used for an accelerated forward motion to travel longer distances. Our within-subject study reveals that our concept effectively avoids cybersickness while enhancing physical activity and presence.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Gestural input**; • **Software and its engineering** → *Virtual worlds software.*

KEYWORDS

virtual reality, locomotion technique, movement, navigation, travel, gesture, cybersickness

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1 INTRODUCTION

The ability to move in virtual environments is essential for most VR scenarios. It allows users to explore extensive worlds, move to specific points of interest, or search for new locations [45, 72]. Numerous locomotion techniques have been established, compared, and refined in recent years, each with different characteristics. The optimal navigation concept is highly dependent on the particular use case and requires considering properties of both the virtual and real environments. Among these factors, limited physical tracking space is a common constraining peculiarity since it prohibits the use of highly natural and immersive locomotion concepts, such as real walking, redirection techniques, or hardware approaches.

Therefore, developers tend to rely on virtual locomotion techniques, such as teleportation, which have only very minimal requirements in the form of a tracked controller. Whereas these concepts work well for stationary setups, they often fail to convey the same feeling of realism and presence known from real walking [77]. Another famous approach is walking-in-place, where users perform a walking motion on the spot. This technique increases the feeling of movement and prevents cybersickness typically observed with continuous virtual motions [54]. However, the downsides include additional hardware requirements and an unintended drift of the users' position in the tracking space [54], which is especially critical in stationary setups. Prior research demonstrated that this drift is best avoided by relying on techniques where the users' feet stay in contact with the ground.

This work focuses on two similar gesture-based locomotion techniques that fulfill this criterion and work with the default VR hardware: arm-swinging [44, 56, 86] and point-tugging [15]. For the first technique, users swing their arms in a smooth motion just like they would during a walk, determining the desired walking speed and direction. This concept was generally enjoyed by users [12] for feeling natural [52], not causing cybersickness [15], and being less exhaustive than the traditional walking-in-place [56]. However, prior research suggests poor precision, leading to additional repositionings for local object interactions [9]. Consequently, arm-swinging is best used for traveling long distances and should be accomplished by another locomotion technique for precise maneuvering. With the second concept, point-tugging [15], users employ their controllers to grab the "air" in front of them and pull themselves forwards, similar to dragging oneself along an invisible rope. The reported benefit is easy and free movement in all directions, especially for local navigation [9]. However, longer distance travels were perceived as tedious due to the limited physical speed [15]. Also, this concept induced significantly more cybersickness [15], which may be rooted in the additional physical demand [9].

Considering the characteristics of both concepts, we assume that both locomotion techniques complement each other well to

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benefit from individual strengths. Our presented locomotion approach combines the two techniques for a novel, intuitive, and effective navigation experience. Users of our concept employ point-tugging for local navigation by dragging the environment in front of their chests. Lowering the arms to the waist and moving them in a swinging motion activates an accelerated and smoothed forward movement respective to the users' view. Thereby, we combine the strengths of both techniques into a cohesive experience. Furthermore, the seamless switch between both modes mimics a natural arm position. Typically, many objects in virtual environments are located at chest height to ease interaction. On the other hand, most people would swing their arms around waist height while walking. By using the controller height for switching between both locomotion techniques, we intend to reduce the necessary cognitive workload.

We validate our presented navigation concept against the popular point-and-click teleport, one of the most commonly-used locomotion techniques for stationary setups. Therefore, we use an immersive scenario featuring a search and navigation task. Our experiments reveal that all subjects could navigate the virtual scenario effectively regardless of the chosen locomotion technique, even though our gesture-based concept is slower than the instant teleport. Also, no one suffered from notable cybersickness symptoms. Additionally, the study shows that whereas our approach requires increased physical effort and imposes a greater challenge, our subjects mostly welcomed these aspects. Finally, we confirmed that our presented concept boosts the experienced presence significantly. In sum, the main contributions of our work are the following:

(1) a novel navigation approach combining arm-swinging and point-tugging for precise and effective long- and short-distance travel
(2) a within-subject study to compare the performance and reception of our locomotion technique against the predominantly used teleport.

2 RELATED WORK

In this section, we introduce the current state of research on VR locomotion. We focus primarily on gesture-based techniques related to our presented concept and also include a brief paragraph on cybersickness.

The range of available locomotion techniques has been ever-expanding in the last decades, leaving us with a broad field of movement concepts targeting different use cases. To preserve legibility, we limit our overview to the critical advancements related to our work and point to the plethora of taxonomies and reviews summarizing the state of research [3, 6, 7, 19, 40].

Among the various kinds of VR navigation, natural walking [63] takes a key role, promising intuitive and presence-preserving movement. Most modern headsets, such as the Oculus Quest [20], come with room-scale tracking, allowing users to explore virtual worlds naturally by foot. However, the requirements to the physical tracking space severely limit the practical applicability for larger scenarios. Therefore, research has concentrated on developing novel locomotion techniques that preserve similar characteristics while providing effective long-range locomotion without causing cybersickness or exhaustion.

Virtual travel techniques decouple the real and the virtual movement to achieve unlimited range. However, one common problem of such locomotion approaches involving continuous virtual locomotion without a physical counterpart is cybersickness [26, 66]. This adverse effect is usually prevented by using brief and fast movements without acceleration [13, 46, 89] or discrete translations [21, 61]. The most prominent representative of this category is undoubtedly the instant teleport [11]. It is easy to use and does not cause cybersickness [24]. However, it has been argued that the instant relocations might break the players' presence [10] and limit the users' ability to estimate the traveled distance [4, 10], causing spatial disorientation [8]. Apart from teleportation, dozens of other virtual locomotion techniques have emerged over the years. Notable examples include the world-in-miniature concept [17, 70] or the use of portals to switch between different scenes [30, 68, 69]. Other approaches combine discrete translations with short continuous motions to improve the navigation experience [2, 5]. Nevertheless, virtual locomotion in general still has not yet reached the same level of naturalness and intuitiveness as actual walking [77].

Therefore, past research has developed several concepts that are based on real walking but extend the available walking range. The most renowned approaches in this category are redirection techniques [50, 71], such as redirected walking [58, 59], which unconsciously reroute users by deviating the visual image from the actual movements through translational and rotational gains [25]. The result is an improved walking experience with fewer required resets [37] and overall reduced collisions with the physical environment [85]. Other work instead used overt approaches such as reorientation portals [23, 43, 47] or bent virtual environments [64] for similar effects.

Apart from reorienting users toward the tracking space's center, another category of walking extensions focussed on scaling users in the virtual world to allow them to cover larger distances [36] or create believable virtual locomotion for long journeys [14]. Similarly, the opposite approach has also been established in the form of walkable minimaps of the surrounding scenario [39]. Finally, the third type of locomotion technique is based on accelerating the users' movements in the virtual world. Most of the prior research has dealt with faster walking speeds [32, 62, 74, 88], with one exception focussing on scaled jumps [8]. Such approaches limit the movements' scaling to the forward motion alone as accelerated lateral movements induce cybersickness. For an in-depth review of other walking-based locomotion techniques, we point to the extensive work by Nabiyouni and Bowman [49].

2.1 Gesture-based Movements

Even the most effective locomotion concept to extend the available walking range requires at least a few square meters of tracking space. Consequently, such approaches are not suited for minimal stationary setups. The category of gesture-based navigation techniques mainly targets these cases. Despite not involving any real walking, these concepts seek to convey a better navigation experience than comparable controller-based approaches, such as the discrete teleport. The main idea is to use walking-related movements, such as arm swings or walking on the spot, to trick the human brain into a walking impression. These motions should provide a greater degree of realism and reduce adverse side-effects such as cybersickness [15, 52].

During the design of gesture-based locomotion techniques, a particular focus is usually on spatial orientation, which is the human ability to perceive the body's orientation and position relative to the surrounding environment [83, 84]. Therefore, humans rely on visual and proprioceptive cues while moving in an environment [80]. Past research has indicated that virtual environments tend to reduce the users' spatial orientation [57]. Whereas the underlying effects are not yet fully understood, the observations are likely to be caused by differences in the perception of motion and environmental cues necessary for maintaining a proper spatial orientation. In particular, virtual locomotion techniques usually suffer from such detrimental effects, and physical walking has been shown to elicit the best spatial awareness [18]. Therefore, gesture-based navigation concepts aim to transfer the positive effects from walking to stationary virtual travel.

A prominent example of gesture-based locomotion is the walking-in-place technique [65, 75]. Instead of walking physically through the tracking space, users perform steps on the spot, mimicking the natural walking pattern. However, early implementations did not feel as familiar as real walking [77] and came with various drawbacks: Due to the used technologies, some concepts required a warm-up phase of multiple steps [65], suffered from a noticeable step lag [82], or required additional hardware, such as Kinect sensors [83] or other motion capturing systems [73]. Later research focussed mainly on the detection algorithms, for example, by considering the biomechanics of human gait [81].

Another drawback of many walking-in-place approaches is the so-called Unintended Positional Drift (UPD) [53]: Users who travel through virtual environments by walking-in-place tend to move physically in the direction they face in VR. This side effect is particularly detrimental to the user experience, as walking-in-place is usually applied to counter the physical constraints of a stationary setup. Thus, users should not move in reality to avoid collisions. Whereas gradual feedback to the users effectively reduces the overall UPD [54], the optimal solution remains using walking-in-place gestures where the feet stay in contact with the ground [51].

One gesture-based locomotion technique similar to walking-in-place that fulfills the above criterion is arm-swinging [44, 56, 86]. Users swing their arms just like they would during a walk. The algorithm uses this motion to detect the desired walking speed and direction. A similar concept, arm-cycling [15], also allows users to move their arms in circles to move forward in their yaw-direction. Past research has compared arm-swinging against other commonly used locomotion techniques. Nilsson et al. [52] report this concept feels more natural than walking-in-place. Also, it offers superior spatial orientation and similar cybersickness levels compared to the instant teleport [15]. However, Bond et al. [9] note the poor precision that leads to additional cumbersome repositionings to interact with objects. Finally, compatibility with other interactions, such as grabbing items, is deemed an issue as most implementations involve continuous gesture-detection [52].

The second gesture-based locomotion approach that inspired our presented movement concept is point-tugging [15]. With this navigation technique, users move their controller in front of themselves and lock it to a point in space by pressing a button. By pulling the controller towards themselves, users can move forward in the virtual world. This research was originally inspired by the game "tug of war" and resembles pulling one's body along an imaginary rope. Even though the concept performed better than teleportation in terms of spatial orientation, users criticized the technique for being exhaustive and causing cybersickness. The last aspect was assumed to be severed by the implementation of point-tugging, which used view-independent movement. Like this work, many gesture-based locomotion concepts use the controllers' orientation to determine the users' intended travel direction and allow them to look around while navigating. However, Williams et al. [83] compared using torso versus gaze direction for walking-in-place implementations and found that whereas the torso condition mimics real walking better, it was deemed more disorienting. Using the gaze direction was preferred by most users and provided an overall better spatial orientation.

2.2 Cybersickness

One of the most prevalent issues of many locomotion techniques is the occurrence of cybersickness [29, 38]. Despite causing partly similar symptoms like simulator sickness [34, 35, 67], both are considered separate strains of the motion sickness phenomenon and differ in causes and effects [48, 55]. Cybersickness is generally caused by a sensory input mismatch between the human vestibular and visual systems [38], leading to severe symptoms such as disorientation and nausea [60, 67]. In particular, the perceived vection [28] and optical flow rate [41], mainly induced by nearby moving objects, are assumed to be closely linked to the formation of cybersickness. Apart from comfort options, such as the limitation of the field-of-view [22, 42], which reduces the optical flow, research has also indicated that cybersickness might not be necessarily detrimental to user experience [78].

3 LOCOMOTION CONCEPT

Our presented locomotion concept *Tug & Swing* combines arm-swinging and point-tugging for effective long-distance travel and precise maneuvering. Therefore, we include two distinct states that are distinguished by the users' arms position (see Figure 1). When users raise their arms in front of their chests, they can use point-tugging to drag themselves precisely through the virtual environment. Lowering the arms to hip height enables faster travel with a combination of arm-swinging and point-tugging. We learned from early prototypes that a cutoff point at 75% of the headset's height works well across different body types. In both modes, users rotate by turning in the real world.

3.1 Local navigation using point-tugging

Similar to the point-tugging concept by Coomer et al. [15], we provide a locomotion approach for close-range navigation. Therefore, the users raise their hands in front of their chest. Upon pulling the VR controller's trigger, its position in relation to the tracking space origin is saved. Until they release the trigger, the users can drag themselves freely around in the virtual environment. At every frame, their position is updated by the difference between the current pos_c and the last controller position $lastpos_c$. This movement is limited to the x-z-plane so that the users remain placed on

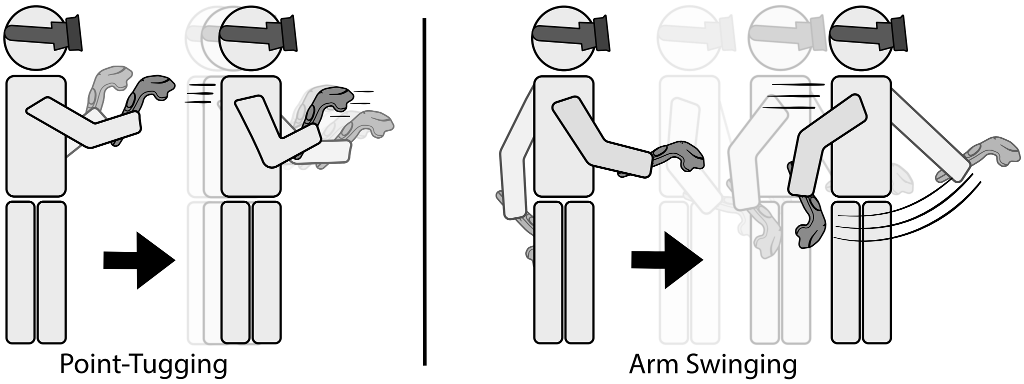

Figure 1: The two modes of our locomotion technique. Left: users perform point-tugging at chest height for local navigation. Right: grabbing and swinging the arms at waist level activates an accelerated forward motion for long-distance travel.

the ground. Additionally, the virtual movement speed matches the actual hand movements precisely and permits navigation in every direction. This locomotion mode is primarily intended for local navigation as it allows the users to reach targets located within close proximity precisely. However, past research has shown that this technique is too tedious for extended travels and that the constantly changing velocity tends to induce cybersickness.

3.2 Accelerated locomotion for longer distances

Apart from the local navigation approach, our concept also includes a dedicated locomotion mode for distant travel. Therefore, the users lower their arms at their waist level and perform large arm-swinging movements. Comparable arm-swinging implementations [44, 56, 86] tend to use the controller speed to calculate the forward movements continuously until the users stop the motion. This approach of not using a dedicated activation input from the users reduces the necessary complexity. However, it limits the practical applicability as the developers must allow for accidental and unintended movements induced by users gesturing or interacting with the environment. Internal tests with other members of our group led to the development of a different approach: As our first locomotion mode already uses the grab-the-air metaphor of point-tugging, we extended this concept to the arm-swinging implementation as well. Similar to the local navigation, the users activate the movement by pressing the controllers' triggers in front of them, performing an arm-swing, and releasing the triggers behind the body. This interaction requires a short adaptation phase, but the users quickly learned to time the movements fluently for fast and effective traveling. This arm-swinging motion feels like dragging oneself along two horizontal ropes besides the body.

Whereas this concept already speeds locomotion considerably, it remains a hybrid of arm-swinging and point-tugging and is therefore likely to be significantly more exhaustive than purely virtual locomotion techniques in the long run. Therefore, we added another acceleration feature to this second locomotion mode, mainly intended for extended travels. Instead of just using the controllers' motions, as done in the first mode, we accelerate the movement depending on the arm-swinging velocity. Swinging faster would therefore lead to further advancements with every swing. In an iterative design process with three participants, we evaluated different movement speeds. Aiming for broad applicability among novice users, we decided to cap the maximal boost to avoid unintended and confusing movements. Also, the velocity must exceed a predetermined threshold so that slower hand movements are not accelerated but perform similar to the local point-tugging. After multiple iterations, we decided to boost the original arm-swinging movement according to the following formula (v_c is the controller's velocity in the forward direction):

$$boost_{forward} = \begin{cases} 1.0 & \text{if } v_c \leq 1\, m/s \\ 5.0 & \text{if } v_c \geq 3\, m/s \\ 2\,v_c - 1 & \text{otherwise} \end{cases}$$

Whereas the Tug & Swing concept already allows effortless long-distance travel and should therefore be of low impact for users, the used movement acceleration might result, as past research suggests, in increased cybersickness symptoms. To prevent a poor user experience, we did not use the swing direction of the arms to determine the intended forward vector but limited the accelerated movement in the travel mode solely to the headset's direction. This decision has been shown to benefit spatial orientation and reduce the risk of cybersickness [83]. Also, the forward direction is smoothed over multiple frames to remove small head-bobbing related motions that are natural for human movement but could induce artifacts while traveling. Both modifications are used only for the travel mode as the local point-tugging mechanic is designed to provide free locomotion regardless of the viewing direction.

In sum, our locomotion technique is a novel combination of two well-known navigation approaches: arm-swinging and point-tugging. It aims to provide free local movement and effortless and effective long-distance travel without causing fatigue or cybersickness. This concept works in a minimal tracking space and is therefore mainly suited for limited setups.

4 EVALUATION

We conducted a user study in our VR lab to evaluate the properties of our presented hybrid navigation approach. As we designed Tug & Swing mainly for stationary setups with limited tracking space, its direct competitor would be a virtual locomotion technique. Such techniques have minimal space requirements but are usually worse in terms of presence and naturalness. The most commonly used representative in this category is the instant teleport. Therefore, we aimed to determine the qualitative and quantitative differences between teleportation and our approach using a futuristic virtual scenario. To assure comparability and reproducibility, we derived our hypotheses from the eight performance metrics for locomotion techniques proposed by Bowman et al. [6]:

User Comfort. Whereas past research sometimes reported the occurrence of cybersickness with similar gesture-based locomotion techniques [15], we designed our combinative concept especially with this characteristic in mind. Using point-tugging only for local locomotion and binding the direction of the accelerated travel to the users' view, we are confident to minimize the risk cybersickness.

Speed and Accuracy. In contrast to the point-and-click teleport, our concept does not feature instantaneous traveling. Therefore, we assume an overall slower movement speed. However, given that walking-inspired navigation concepts usually improve the users' spatial orientation, we assume that the total travel distance, which reflects the accuracy, does not differ significantly.

Ease of Learning and Ease of Use. An essential characteristic of every locomotion technique is learnability and usability. Users must quickly get accustomed to the controls to navigate effectively in virtual scenarios. Both of our compared locomotion concepts use just one button. With our concept, users hold a button to grab the environment and pull themselves forward. For the teleport, users initiate a target pointer upon pressing a button and release it for teleportation. Despite this similarity in interface complexity, both techniques differ greatly in the underlying interaction concept. Teleporting is a purely event-driven task, making it easy to attribute relocations to individual input actions. On the other hand, our gesture-based technique is motion-driven and continuously translates the user's actions into virtual movements. Even though this design adds another layer of complexity, we believe that the natural motions mimicking real walking still guarantee good learnability and usability. Consequently, we assume that our technique compares well against the teleport, known for its simplicity.

Spatial Awareness and Information Gathering. Real walking helps users generate a cognitive map of the surroundings and thus leads to improved spatial awareness and a better impression of the environment. Even though our movement concept mimics real walking only through gestures, we still assume that it outperforms the purely virtual teleport concerning spatial orientation.

Presence. Finally, VR experiences are usually designed to be enjoyable and elicit a strong feeling of presence. The used locomotion technique should reflect these properties and avoid breaking the users' presence. In contrast to the discrete teleportation, our Tug & Swing concept allows for smooth continuous locomotion and resembles real walking. Therefore, we assume that it fosters the experience of being present in the virtual scenario.

To summarize, our hypotheses are:

- H1: The presented Tug & Swing concept does not induce significant cybersickness.
- H2: Both locomotion concepts do not differ significantly in travel accuracy, but the Tug & Swing concept increases the travel time.
- H3: Both conditions do not differ significantly in usability and learnability.
- H4: Tug & Swing provides significantly better spatial orientation than teleportation.
- H5: Compared to teleportation, Tug & Swing significantly increases the perceived presence.

4.1 Testbed Scenario

We realized our testbed scenario using the Unity game engine [76]. The scene is set in a futuristic indoor environment consisting of multiple rooms and corridors filled with technical equipment that impedes locomotion and forces the users to navigate the environment carefully. The users start the scenario at a predefined starting position and must reach the level's exit. Whereas signs mark the exit's location, the users must first open two locked doors. Therefore, they activate one, two, or three switches spread across the environment. Each door has lights indicating the number of remaining inactive switches.

Brown tubes connect the door and the switches to assist the users with finding the switches and eliminating chance. However, these tubes are often partially occluded by cargo and other blocking objects. Upon reaching a switch, the users activate it with a simple touch and then return to the door for the next switch or pass on to the next area. After unlocking the final door and entering the elevator that serves as the final destination, the level ends.

This level design forces the users to explore the environment actively to solve the given informed-search task. They must follow the tubes, which requires a good mastery of the locomotion technique, and later need to return to the door challenging spatial orientation. As we aimed for a within-subject study, we designed two similar levels L1 and L2, to eliminate learning effects. Both levels are designed identically and vary only in the layout of the corridors (see Figure 2). The required distance between the different switches and doors is identical on both levels ensuring good comparability between the scenarios.

4.2 Procedures and Applied Measures

We conducted a within-subject study to compare our Tug & Swing technique with the instant teleport. Additionally, we avoided sequence effects by applying a cross-over design, i.e., splitting the subjects into two groups, each starting with one locomotion technique and using the other in the second round. Further, we wanted to avoid repetition effects through learning the environment or task. Therefore, we alternated the order of levels, resulting in four combinations that were counterbalanced with a Latin square design.

We conducted the study, which took 30 minutes on average, in our $16m^2$ VR lab using a Quest 2 [20]. First, the subjects were informed about the general procedure and the unique circumstances of VR experiences and signed an informed consent form. Then, we assessed general information, such as gender, age, prior VR experience, and gaming habits. After these preliminary steps, we

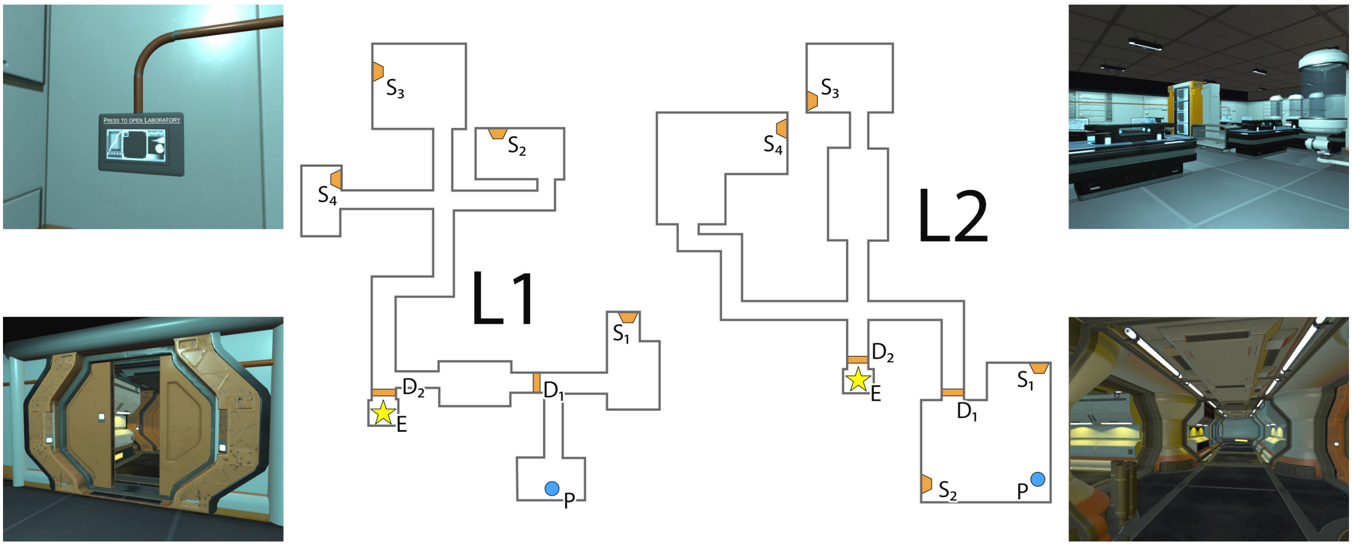

Figure 2: Overview of the two levels $L1$ and $L2$ of our testbed environment for the study. Marked are the starting positions (P), the doors (D), the switches to unlock the doors (S), and the levels' exits (E).

introduced the subjects to the VR hardware, mainly the headset and the controllers, and assisted them in adjusting the fit properly.

After all technical issues and questions were resolved, the subjects started the scenario in a waiting room, where they received their instructions. As part of this introduction, the subjects were shown the locomotion technique and could try it briefly before starting the first round. Finally, the actual level started. Throughout the playthrough, we logged the relevant statistics needed for our hypothesis H2, such as the locomotion distance and travel duration. After completing this first level, the subjects completed a set of questionnaires assessing their personal experience.

For H1, we tested for potential cybersickness effects using the Simulator Sickness Questionnaire (SSQ) [33], which consists of the three subscales, *nausea*, *oculomotor*, and *disorientation*, with a scale from 0 (none) to 3 (severe) for the individual items. Further, we assumed that both concepts do not differ regarding their usability. Therefore, we administered three subscales of the Player Experience Inventory (PXI) [1]: *ease of control*, *challenge*, and *mastery* (all coded -3 - 3). Also, we included the two items *mental demand* and *physical demand* of the NASA Task Load Index (NASA-TLX) questionnaire [27], to ensure that our gesture-based locomotion technique is not overly demanding. These subscales are rated on a 100-point scale with 5-point steps (coded 0-99). Next, we added the Presence Questionnaire (PQ) [16, 87] to quantify the influence of the navigation concepts on the perceived presence. The PQ consists of the five subscales *realism*, *possibility to act*, *quality of interface*, *possibility to examine*, and *self-evaluation of performance* (coded 0 - 6). The questionnaires were complemented by eight custom questions (coded 0-6), covering further locomotion-related aspects such as spatial orientation. After completing this first round of questions, the subjects returned to VR for the second level. Following this playthrough and the second set of questionnaires, subjects could finally share their thoughts in semistructured interviews.

5 RESULTS

According to a preliminary power analysis, with a significance threshold of $\alpha = .05$, we aimed for a sample size of $N = 20$ to detect medium effects (effect strength: $d = 0.7$) with 80% power. This choice was mainly determined by external organizational factors, especially the COVID-19 pandemic, and lessons learned from other recent studies. We recruited 20 subjects (5 female, 15 male) among university students and personal contacts. The subjects with a mean age of 24.5 (SD=7.28) mainly had already used VR setups before (75%) and reported playing digital games regularly (95%).

In our within-subject study, we compared our presented locomotion technique Tug & Swing to the instant teleport. Therefore, we used a pair of similarly structured levels and randomly split the subjects into four groups to avoid repetition effects. Each group started with one locomotion technique and one level and played the opposite combination after that. Before testing our hypotheses, we confirmed comparability between both levels to eliminate possible confounding differences. Therefore, we grouped trials sharing the same locomotion technique and tested for significant variations of playtime and travel distance. Neither the average level completion time ($time_{L1}$ = 347.09 (SD=44.79); $time_{L2}$ = 362.19 (SD=20.40); $t(14.547) = .999$; $p = .334$; 95% $CI[-17.22, 47.41]$) nor the traveled distance ($distance_{L1}$ = 819.31 (SD=38.05); $distance_{L2}$ = 851.87 (SD=93.85); $t(18) = 1.055$; $p = .306$; 95% $CI[-32.30, 97.43]$) differed significantly for the teleport condition. The same also accounts for the playtime ($time_{L1}$ = 580.06 (SD=188.86); $time_{L2}$ = 583.96 (SD=340.95); $t(18) = -.031$; $p = .976$; 95% $CI[-271.72, 263.90]$) and the distance ($distance_{L1}$ = 886.26 (SD=90.13); $distance_{L2}$ = 866.68 (SD=57.35); $t(18) = .591$; $p = .562$; 95% $CI[-50.05, 89.21]$) in the Tug & Swing condition.

Given this comparability between the two levels, we treated both scenarios equally and compared the assessed measures between the within-conditions Tug & Swing and teleport using paired sample

Table 1: Mean scores, standard deviations, and paired sample t-test values of the Presence Questionnaire (PQ), the Player Experience Inventory (PXI), the NASA Task Load Index (NASA-TLX), and the Simulator Sickness Questionnaire (SSQ).

	Tug & Swing M(SD)	Teleport M(SD)	$t(19)$	p		d	CI
PQ (scale: 0 - 6)							
Realism	4.60 (1.05)	3.93 (1.29)	3.621	.002	**	.810	[.283, 1.060]
Possibility to Act	5.16 (0.71)	4.81 (0.63)	3.243	.004	**	.725	[.124, .576]
Interface Quality	5.25 (0.80)	5.35 (0.55)	-.474	.641		-.106	[−.542, .342]
Possibility to Examine	5.08 (0.70)	5.02 (0.41)	.677	.507		.151	[−.140, .273]
Performance	5.30 (1.22)	5.78 (0.38)	-1.758	.095		-.393	[−1.040, .090]
Total	4.97 (0.76)	4.71 (0.67)	2.211	.040	*	.494	[.014, .517]
PXI (scale: -3 - 3)							
Mastery	2.42 (1.13)	2.30 (0.92)	.733	.472		.164	[−.216, .450]
Ease of Control	2.27 (0.63)	2.65 (0.71)	-1.792	.089		-.401	[−.831, .064]
Challenge	1.20 (1.48)	-0.27 (1.73)	5.174	.001	**	1.157	[.873, 2.060]
NASA-TLX (scale: 0 - 100)							
Mental Demand	41.00 (30.20)	33.00 (27.02)	1.675	.110		.375	[−1.998, 17.998]
Physical Demand	42.25 (21.85)	5.75 (12.38)	7.279	.001	**	1.628	[26.005, 46.995]
SSQ (scale: 0 - 3)							
Nausea	8.59 (21.42)	7.16 (10.21)	.403	.691		.090	[−5.994, 8.856]
Oculomotor	3.41 (6.26)	5.69 (6.90)	-1.301	.209		-.291	[−5.932, 1.384]
Disorientation	9.05 (17.65)	9.05 (11.31)	.000	1.000		.000	[−7.010, 7.010]

$^{*}p < .05$, $^{**}p < .01$

t-tests. Therefore, we assured that the test's assumptions were met by testing for normal distribution with Shapiro-Wilk tests. This section reports the t-tests' results, including strengths of the effects and confidence intervals necessary for reproducibility [79]. All calculations were performed using IBM SPSS 27 [31].

5.1 Questionnaires

For our first hypothesis, H1, we assessed the SSQ, whose results are listed in Table 1. According to the reference values by Kennedy et al. [33], no subject experienced notable amounts of cybersickness. Both conditions performed similarly, and the small confidence intervals of the means reinforce the absence of any undiscovered meaningful effect. Next, we administered the PQ to determine the conditions' influence on presence. Whereas most subscales are similar, the scores for realism and possibility to act are higher for the Tug & Swing condition. T-tests suggest a large statistically significant effect according to Cohen's d. Also, the score for total presence is significantly higher, indicating a medium effect.

Further, we assessed three subscales of the PXI. Subjects generally rated mastery and ease of control high for both techniques. Only the challenge subdimension differs significantly, as the Tug & Swing condition is considered more challenging. This result corresponds to a large effect. Finally, we measured two subscales of the NASA-TLX. Both items, mental demand and physical demand, are higher for our presented concept. However, only the difference in physical demand shows a large statistically significant effect. Whereas subjects rated the teleport technique only minimally demanding, our gesture-based technique required a considerable physical effort.

5.2 Custom Questions

We closed the questionnaires with eight custom questions to deepen our understanding of the compared locomotion techniques and answer our hypotheses. These covered usability issues (CQ1-CQ3), physical activity (CQ4 & CQ5), spatial orientation (CQ6), and personal reception (CQ7 & CQ8). Table 2 shows the results for all questions. Except for CQ1 and CQ6, all values imply medium to large statistically significant differences. Both techniques rarely caused any difficulties (CQ1, CQ3) and were easy to learn (CQ2); however, only the teleport received maximal ratings. In turn, it appears that subjects felt more active when using our presented approach (CQ4), which required more effort (CQ5), but felt less monotonous (CQ7) and illogical (CQ8). The ratings for spatial orientation did not differ between both conditions.

5.3 Logging Data

We logged the traveled distance, playtime, and the count of grabs and teleportations throughout the two played rounds (see Figure 3). These data are mainly needed to test our hypothesis H2. The average playtime for the Tug & Swing condition is 64.8% higher compared to the teleport condition. This difference is statistically significant ($t(19) = 3.784$; $p = .001$; $d = .846$; 95% $CI[102.036, 354.604]$) and indicates a large effect. Similarly, the data also indicate a medium statistically significant effect between the traveled distance in both conditions ($t(19) = 3.071$; $p = .006$; $d = .687$; 95% $CI[13.524, 69.833]$). According to the means, subjects traveled 4.98% more with our technique. Finally, we also compared the number of times subjects had to use the teleport or a grab interaction. The data reveal that 91.16% more point-tugging and arm-swinging gestures were necessary to cover the distance. This difference indicates a large statistical effect

Table 2: Mean scores, standard deviations, and paired sample t-test values of the custom questions (CQ).

Question Item	Tug & Swing M(SD)	Teleport M(SD)	$t(24)$	p	d	CI
CQ1 I had difficulties getting where I wanted.	1.80 (1.64)	1.00 (1.65)	1.341	.196	.300	[−.448, 2.048]
CQ2 The controls were intuitive and easy to learn.	5.10 (1.29)	6.00 (0.00)	-3.111	.006 **	-.696	[−1.505, −.295]
CQ3 I had problems with the controls.	1.40 (1.79)	0.00 (0.00)	3.500	.002 **	.783	[.563, 2.237]
CQ4 I felt very active while playing.	5.00 (1.41)	2.50 (1.99)	4.756	.001 **	1.063	[1.400, 3.600]
CQ5 I felt that too much effort was needed to reach the different locations.	1.65 (1.81)	0.40 (0.68)	3.206	.005 **	.717	[.434, 2.066]
CQ6 I could orient myself well in the virtual world.	5.40 (0.50)	4.95 (1.43)	1.443	.165	.323	[−.203, 1.103]
CQ7 Traveling the virtual world felt very monotonous.	2.50 (1.79)	3.60 (1.79)	-2.979	.008 **	-.666	[−1.873, −.327]
CQ8 I think the locomotion technique was illogical.	0.65 (0.93)	2.30 (1.95)	-3.776	.001 **	-.844	[−2.565, −.735]

$^{*}p < .05$, $^{**}p < .01$

($t(19) = 6.314$; $p < .001$; $d = 1.412$; 95% $CI[125.478, 249.922]$) and shows that subjects traveled on average 4.05m with each teleport, whereas a single gesture corresponds to only 2.22m.

6 DISCUSSION

All subjects, who participated in our study, were able to navigate the scenario using both techniques and complete all required tasks. Subjects, who had already experienced VR games before, were often already familiar with the instant teleport. Also, a significant number of subjects mentioned previous experiences with locomotion-related issues that were mostly connected to cybersickness induced by virtual motions. Such problems did not arise during study execution, and as most subjects enjoyed their participation, they were eager to share their personal opinions in the concluding interview session. In this section, we discuss our gained quantitative and qualitative insights towards the various hypotheses.

H1: The presented Tug & Swing concept does not induce significant cybersickness.

According to the mean values of the SSQ, the subjects did not experience any notable cybersickness symptoms throughout the study. Also, there were no detectable differences between both conditions. This last finding is especially notable, as the teleport is usually chosen as a comfort option for susceptible users. Moreover, past research has reported that especially point-tugging tends to foster the formation of cybersickness. However, it was assumed that this adverse effect is mainly connected to excessive physical expenditure. We countered this issue by using precise point-tugging only for maneuvering and accelerated arm-swinging for long distances. In the end, our study's results support the assumption that this combination effectively prevents cybersickness.

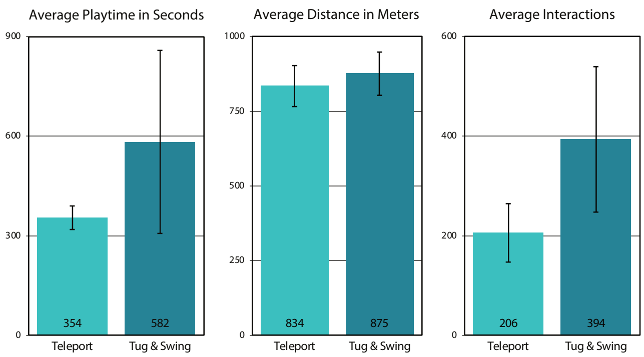

Figure 3: Results from the data logged during the study. Left: the travel time for both conditions in seconds. Middle: the average distance (in meters) subjects traveled in the virtual world. Right: the average interaction count (teleports/grabs) performed in both conditions.

H2: Both locomotion concepts do not differ significantly in travel accuracy, but the Tug & Swing concept increases the travel time.

In H2, we assumed that the overall travel time would increase, whereas the travel accuracy, quantified by the traversed distance, remained the same. The data logged during the study confirmed the first part of the hypothesis: the average travel time in the Tug & Swing condition is almost doubled. This result is easily explained by the different nature of the locomotion techniques, as gesture-based traveling does not permit instant relocations and thus requires more time. However, the average traversed distance was also significantly higher. Even though this finding invalidates the other part of our hypothesis, it is essential to consider the actual difference in means and discuss the practical implication of the finding. According to the logged data, subjects traveled only 5% further when using Tug & Swing. Also, the 95% confidence interval reveals that the maximal probable difference is at most 8.3%. Thus, we can safely assume that whereas the accuracy is indeed poorer than for the teleport, this difference is small and possibly negligible. Finally, CQ1 confirms that subjects had very few problems with either locomotion concept and could use both to navigate the scenario effectively.

H3: Both conditions do not differ significantly in usability and learnability.

When developing our gesture-based locomotion technique, we aimed for good usability and low complexity to allow users to navigate without a long learning phase. Consequently, we compared our concept against the teleport, which is well known for its simplicity. As one of the most used locomotion techniques, teleportation is probably already known to many subjects with prior VR experience. Thus, it is not surprising to see that the teleport was still outperforming our technique and gained perfect marks concerning intuitive and nonproblematic controls (cf. CQ2 and CQ3). However, despite this significant difference in means, our presented approach also was not perceived as complicated or problematic. The scores of CQ2, CQ3, and the PXI subscales mastery and ease of control demonstrate that the subjects did have no problems navigating with these locomotion concepts. Oral feedback from subjects supports these results: *"I could quickly reposition myself by pulling in front of me - this was especially useful when I traveled a bit too far"(**P16**).*

A major difference between the conditions revealed by our quantitive data is the increased physical demand that comes with a gesture-based technique like ours. Compared to the minimalistic teleport, it involves a large arm movement that subjects must execute significantly more often to traverse the same distance. This characteristic increases the overall effort, as seen in the respective item of the NASA-TLX, and might also explain the difference in the PXI's challenge subscale. In the past, research has indicated that cumbersome locomotion techniques can easily frustrate users and cause cybersickness and early exhaustion. To assure that this is not the case, we added the two custom questions CQ4 and CQ5. In line with the earlier results, CQ4 reveals that users felt far more active using the gesture-based technique. However, despite being reported as more cumbersome than the teleport condition (see CQ5), the overall low means for both conditions do not indicate a severe exhaustion problem: *"Whereas the arm-swinging was more physically challenging, it did not feel cumbersome but instead increased the overall realism of moving through the corridors"(**P3**).*

H4: Tug & Swing provides significantly better spatial orientation than teleportation.

Several past studies have indicated that a walking-based technique helps users orient themselves in the virtual world. In contrast, virtual travel techniques, such as the teleport, are known for their negative effect on spatial orientation. We consider our technique as a mixture that combines walking-inspired movements with virtual locomotion. Therefore, we expected to see better spatial orientation compared to the virtual teleport. Whereas the means of CQ6 signal that users had a slightly better impression of their surroundings while using our approach than with the teleport condition, this effect is not statistically significant and does not confirm our hypothesis. Therefore, we cannot reach a decisive conclusion on whether there is an actual difference. In our future work, we will investigate this important characteristic through additional studies.

H5: Compared to teleportation, Tug & Swing significantly increases the perceived presence.

Finally, we assessed the PQ and additional custom questions to determine potential effects on the users' perceived presence and overall experience. In particular, our presented approach outperformed the teleport condition in the PQ's subscales realism and possibility to act. This finding reveals that subjects gained the impression that the walking-inspired navigation feels more natural and realistic. These traits are reflected in oral feedback from subjects: *"Swinging my arms felt exactly like real walking. I liked especially that the speed corresponded to my arm movements - so I could accelerate the movements, and it felt like running along the corridor"(**P8**).* Also, the difference in the subscale possibility to act indicates that users felt freer in their choice of navigation. *"With the teleport, I just aimed and jumped ahead. Arm-swinging allowed me to use my own pace and style - long and slow swings, short and fast movements, dragging backward or sideward - there was much more variety"(**P14**).* This feedback could also explain the significantly lower values for CQ7, indicating that our concept was perceived as less monotonous.

7 LIMITATIONS

For our study, we compared our Tug & Swing concept against the instant teleport. This decision was motivated by the high prevalence of teleportation in consumer applications and related research studies. Also, its strength, the instant, effortless, and cybersickness-free relocation, makes this technique a perfect competitor to assess the benefits and drawbacks of our gesture-based approach. As a resulting limitation, our chosen study design misses a direct comparison to the predecessors: arm-swinging and point-tugging. However, the original work by Bond et al. [9] and Coomer et al. [15] already compared the individual concepts to teleportation and reported a significantly poorer performance regarding cybersickness, accuracy, and fatigue. Since our study revealed that Tug & Swing performs similarly to the teleport, especially in terms of cybersickness, we confidently assume that it also outperforms its predecessors.

Another limitation lies within the participant base of our study: most subjects were relatively young and overwhelmingly male. Whereas we always aim for a wide range of participants, our main recruitment pool consists of computer science students. Consequently, we emphasize the potential confounding impact of this imbalance on the study's results, as interaction with technology always depends on age and gender. Lastly, our choice of the VR environment for the study could have influenced our results. In such highly futuristic indoor scenarios, participants might find it easier to accept unrealistic locomotion techniques like the teleport.

8 CONCLUSION

Today, developers of virtual experiences can choose from a plethora of locomotion techniques that target different use cases and come with individual requirements. Whereas real walking through room-scale tracking is still considered the gold standard for intuitive and presence-enhancing navigation, a growing body of research focusses on concepts for stationary setups, as these prohibit the use of most other locomotion techniques. A common solution is using virtual-navigation concepts, such as the instant teleport, which work with every setup but usually feel less natural and immersive. On the other hand, walking-inspired locomotion techniques frequently rely on additional hardware and suffer from undesired side effects, such as the unintended positional drift.

In our work, we combined two established gesture-based techniques into a novel locomotion concept: arm-swinging and point-tugging. Our approach includes two distinct modes that are triggered by raising the arms in front of the chest or lowering them to waist level. This design provides both precise local maneuvering and accelerated long-range travel. Our within-subject study confirmed that players could use our technique to navigate the virtual scenario effectively without enduring cybersickness. Also, subjects experienced higher levels of presence and felt more active while moving through the virtual world. In essence, our presented concept is mainly suited for limited stationary setups, where real walking is no option, and for scenarios that profit from the benefits above without requiring maximal performance.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	**Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments** *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put…": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments

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Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments

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***Abstract*—Driven by the games community, virtual reality setups have lately evolved into affordable and consumer-ready mobile headsets. However, despite these promising improvements, it remains challenging to convey immersive and engaging VR games as players are usually limited to experience the virtual world by vision and hearing only. One prominent example of such open challenges is the disparity between the real surroundings and the virtual environment. As virtual obstacles usually do not have a physical counterpart, players might walk through walls enclosing the level. Thus, past research mainly focussed on multisensory collision feedback to deter players from ignoring obstacles. However, the underlying causative reasons for such unwanted behavior have mostly remained unclear.**

Our work investigates how task types and wall appearances influence the players' incentives to walk through virtual walls. Therefore, we conducted a user study, confronting the participants with different task motivations and walls of varying opacity and realism. Our evaluation reveals that players generally adhere to realistic behavior, as long as the experience feels interesting and diverse. Furthermore, we found that opaque walls excel in deterring subjects from cutting short, whereas different degrees of realism had no significant influence on walking trajectories. Finally, we use collected player feedback to discuss individual reasons for the observed behavior.

***Index Terms*—virtual reality, game design, virtual walls, locomotion, collisions, player behavior, walking trajectories**

I. Introduction

Exploring extensive virtual worlds is a challenging task. Despite the development of more than 100 virtual navigation techniques, real walking is still considered the gold standard for VR locomotion [1], [2]. Matching the virtual movement to the physical steps offers precise control and assures a realistic and natural experience. However, using the real movement also introduces additional challenges that must be considered in the development phase. Although current headsets, such as Oculus Quest 2 [3], already handle sufficient room-scale tracking of the head-mounted display (HMD) and the controllers, the disparity between the virtual world and the real surroundings remains a problem [4], [5].

These differences between the physical playspace and the VR scenario typically fall into one of two groups: The first are virtual obstacles, such as walls, that do not have a physical counterpart. Most VR setups—except specifically designed lab environments—do not offer matching haptic proxies for the virtual objects [6]. Consequently, players could easily grasp or walk through these immaterial obstacles, which breaks coherency and might spoil the game experience [7]. In the other group fall real obstructions, such as a bench standing in the players' living room, that are not visible to the players but pose an imminent risk of injury [4]. Therefore, current VR systems typically mark the playspace's borders with easily identifiable virtual walls to deter players from leaving this area [8].

Even though the dangers in the second case are much more critical than potential *breaks-in-presence* [9], both types of discrepancies between the real and virtual worlds share a common aspect: Preventing them requires virtual obstacles that the players do not ignore – be it out of curiosity or in the attempt to cut short. Past research has approached this issue by developing various types of auditory, visual, and vibrotactile feedback to notify players of virtual collisions and deter them from willfully ignoring walls [7], [10].

However, up to this point, very little work has addressed the underlying questions: What causes players to not adhere to the virtual world's rules in the first place? Studies have indicated that players might ignore virtual obstacles under specific circumstances [7], [11], but they have mainly focused on simple setups and repeating tasks, such as walking between checkpoints. Other research has shown that players generally tend to conform to the rules in highly immersive experiences [12]. Whether the previously observed collisions are a general phenomenon or are caused by individual properties of the virtual scenario remains unclear.

Therefore, we explored how different task types and appearances of the virtual walls influence the players' incentives to cut short and walk right through the obstacles. Specifically, we conducted a mixed study setup to isolate the observed effects. The participants played a VR game with two similar rounds of carrying objects between checkpoints. For the within-subject part, we varied the task motivation: In one round, the participants had to solve a puzzle by placing different objects on the correct checkpoint. The other round did not offer a similar motive but was designed as a dull and repetitive job. We combined this design with an additional between-subject part: Participants were split into four groups, each being confronted

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with another wall type, differing in the degree of opacity and the degree of realism.

Our results indicate that the given task type has the greatest influence on player behavior. Most participants ignored the walls only in the repetitive round to finish their task faster. In the more diverse and interesting puzzle level, very few subjects collided with a single wall. We conclude that players mostly prefer to stick to realistic behavior and only deviate if getting bored. Furthermore, our experiment reveals that opaque surfaces are highly efficient in deterring players from non-adherent behavior as they feel discouraged from not being able to see behind the wall before walking through. Lastly, our different wall designs had a significant impact on the perceived presence. However, this effect did not influence the players' walking behavior as expected. Apart from testing these three potential factors on collisions in virtual environments, we collected aural feedback from participants to discuss individual reasons for the observed behavior.

II. Related Work

In this section, we summarize the relevant prior research to this work. Therefore, we start by covering the fundamentals of real walking and locomotion in general. Next, we briefly address haptic feedback before discussing the current state of research on virtual collisions and walking trajectories.

A. Walking in Virtual Environments

While non-VR games tend to rely on joystick controls for locomotion, these are less favorable in VR, as purely virtual continuous motion is a key factor leading to cybersickness [13]. Instead, natural walking has emerged as the gold standard among locomotion techniques in virtual environments. Accurately transferring the players' steps into the virtual world not only prevents cybersickness but also feels most realistic and natural [14]. Furthermore, it results in higher presence levels compared to other locomotion alternatives such as walking-in-place [2], [15]. However, natural walking is limited by the play area's physical boundaries, making it challenging to achieve larger explorable virtual environments. Thus, an ever-growing body of research has focused on overcoming this limitation, for instance, by developing novel locomotion metaphors [16] or altering the user's movements unconsciously [5], [17].

B. Haptics and Surfaces

The virtuality of an immersive experience becomes most obvious when players interact with the virtual world and its objects. Touching a wall or grasping an item without feeling a haptic resistance does not even feel close to the familiar multisensorial experience in reality. Therefore, research has focussed on providing surface feedback through passive proxies [18], haptic retargeting [19], electro-tactile feedback [20], or electrical muscle stimulation [21], [22]. Another promising approach, which does not require additional hardware, is the concept of simulated surface constraints [23]: This technique elicits the impression of resistive virtual objects by simply displacing the virtual hand from its real counterpart.

C. Virtual Collisions

According to Blom et al. [10], treating virtual collisions consists of two consecutive parts: collision detection [24] and collision notification. The first aspect, collision detection, is a mostly solved problem in current game engines used for virtual environments. Therefore, this section focuses on the latter problem: Collision feedback not only prevents unwanted penetration of virtual objects, but may also increase the perceived realism [25].

In reality, we usually notice bumping into objects through a haptic response. As haptic reactions are mostly missing in virtual scenarios, research has investigated the effectiveness of a wide variety of other possible feedback channels, including vision, sound, and vibrotactile impulses. Among the first to investigate possible collision behaviors, Jacobson and Lewis [26] altered the users' movement in the virtual world, e.g., by stopping them upon impact. However, such manipulations do not apply to real walking, where the virtual movement is always bound to the physical steps.

Therefore, Bloomfield and Badler [27] examined the use of vibrotactile actuators to convey better collision feedback and found them more effective than purely visual indicators. While they used a shirt-based tactorsuit to convey the collision impressions, other research has achieved comparable effects with different hardware, such as tactile belts [28]. In a similar study, Blom et al. [10] compared vibrotactile feedback using their haptic floor with sound- and controller-based responses. Even though auditory notifications scored worse than the floor feedback, Afonso et al. [29] found spatial sounds to be well suited for preceding collision avoidance.

D. Walking Behavior

A growing body of research has added evidence to the finding that people tend to act realistically in virtual scenarios that conform to reality. This behavior is particularly seen in situations with high *Place Illusion*, *Plausibility Illusion* [12], and visual realism [30]. These findings also apply to VR movement. Ruddle et al. [31] found that using real walking for locomotion causes users to walk around virtual objects. The observed obstacle avoidance trajectories generally conform to real-world walking patterns [32], [33].

Simeone et al. [4] investigated the effects of different ground textures and virtual obstacles on individual movement behavior. The reported findings are closely related to our research focus: Participants generally hesitated cutting short through immaterial but solid virtual objects. For the case of collisions, Boldt et al. [7] presented a multimodal collision feedback approach combining visual, auditory, and vibrotactile feedback that effectively deters players from ignoring virtual walls. Similarly, Ogawa et al. [11] showed that the body-ownership effect of realistic full-body avatars also discourages users from penetrating walls.

III. Study Design

As explained in the previous section, research has already dealt with possible ways to deter players from walking through walls using multisensory collision feedback or virtual avatars. However, under which circumstances players ignore walls in the first place remains to be investigated. Therefore, we conducted a study to address the identified unclear aspects of wall-related behavior.

A. Research Questions and Hypotheses

Existing studies have mainly relied on strong incentives to cut short by using heavily repetitive and monotonous tasks [7], [11]. Therefore, our first goal was to confirm the players' behavior under more engaging circumstances by using an immersive puzzle-scenario. We hypothesize that more varying tasks lead to fewer wall collisions than repetitve and annoying missions.

Further, it remains unclear whether the type of virtual wall influences the players' incentives to cut short. Is this decision connected to the thematic fitting of the wall? Less well-fitting walls potentially reduce the virtual environment's overall authenticity. Since visual realism is one key factor for conforming behavior according to Slater et al. [30], we assume that abstract walls provoke players to walk through them more often.

Another influencing factor might be the wall's degree of opacity. Viewing the target through an obstructing wall could enforce the players' decision to cut short. Also, this characteristic might decrease the *Plausibility Illusion* [12] and raise the players' impression that the wall is safe to pass through. A similar finding was already reported by Simeone et al. [4]. Thus, we assume that partly transparent walls or obstacles with holes lead to more wall collisions.
In summary, our three hypotheses are as follows:

- H1: Repetitive and monotonous tasks provoke significantly more participants to walk through virtual walls than diverse tasks.
- H2: Participants walk significantly more often through abstract walls than through realistic walls.
- H3: Opaque surfaces deter more participants from ignoring virtual obstacles than partly transparent surfaces.

Apart from these hypotheses, we were also interested in the particular reasons players decide to either ignore walls or follow real-world' rules.

- RQ1: How do players decide whether they pass through virtual walls or walk around them?

B. Wall Design and Testbed Scenario

Based on our hypotheses, the virtual walls used in the study should differ in degree of realism and degree of opacity. Considering these requirements, we decided on four wall designs (see Figure 1). Two of these walls are completely abstract blocks with a uniform color. These obstacles differ only in the degree of opacity, with one wall having 30% and the other 60% opacity. The other two walls are designed to fit the surrounding scenario thematically. One wall is implemented as a solid wood wall, thus resulting in full opacity. The other wall resembles a hedge consisting of twines. Whereas this design still looks realistic, it offers enough holes to look through it and creates a similar opacity effect as the abstract walls.

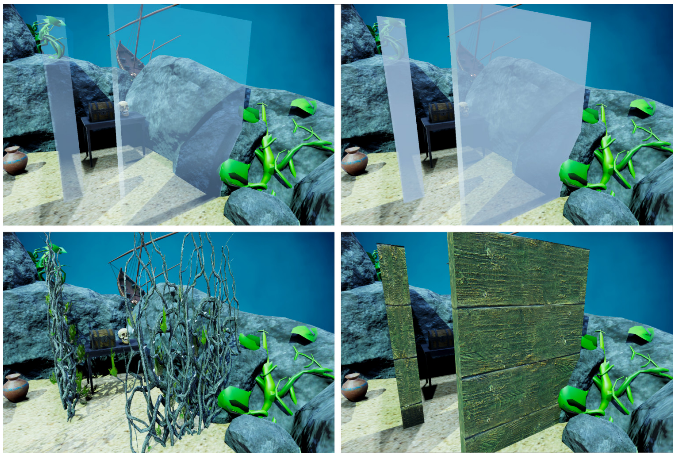

Fig. 1. Our four tested wall designs: Top row: abstract cuboid wall with 30% opacity (left) and 60% opacity (right). Bottom row: twine hedge with holes (left) and opaque wood wall (right), both matching the virtual scenario.

In sum, our four wall designs are:

- A30: Abstract wall design with 30% opacity
- A60: Abstract wall design with 60% opacity
- RTH: Realistic twine hedge with holes
- RWW: Realistic and fully opaque wood wall

Our surrounding testbed scenario was realized with the Unity game engine [34]. The setting is a maritime-themed scenery, featuring boulders and sunken ships (see Figure 2). Since our research focussed on natural walking, we restricted the virtual environment's size to match our lab, i.e., $16\,m^2$. This limited area contains four points of interest and three walls, which – depending on the study condition – match any of the four styles. The walls separate the interaction points so that the players would have to either walk through them or make a detour through the playspace center. We decided against the fourth wall to avoid cluttering the playspace and producing unintended wall collisions.

C. Tasks

Testing H1 required two tasks, one diverse and interesting, and the other highly repetitive. Despite these differences, we still aimed for a similar structure in both tasks and only changed the motivation and reasoning behind the required interactions. Our first task is a simple sequential puzzle. The players carry a single item that must be placed in the correct spot to advance with the task and obtain the next object. For instance, the players may use a key to unlock a chest. They are rewarded with a pearl that must be put into an open shell. These subtasks are chained into complex puzzle of adequate length and require the players to constantly walk between the interaction points.

This task resembles repetitive task designs used in previous studies but adds an engaging motivation and varying interactions, e.g., opening a chest with a key or throwing a coin into a piggy bank. The second task eliminates these diverse interactions. Instead, it is just a simple carrying task. Players must carry a coin in counter-clockwise rotation from one

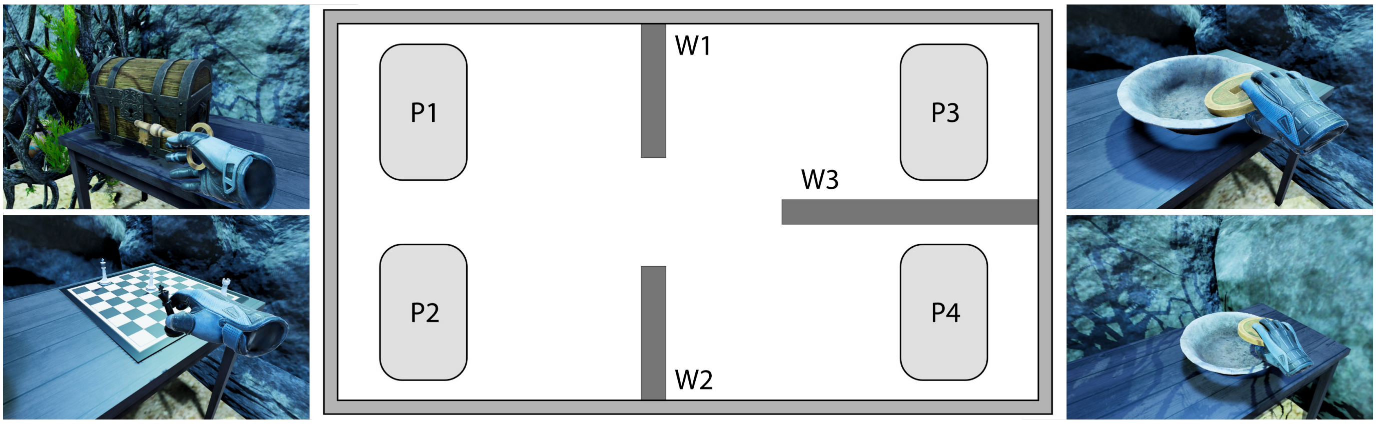

Fig. 2. Schematic map depicting our testbed environment, featuring four interaction points (P1–P4) and three virtual walls (W1–W3). The images illustrate the different activities: in the puzzle task (left), items and interactions vary. In the repetitive task (right), participants only move coins between bowls.

interaction point to the other. Whereas this task resembles the first one regarding movement patterns, it is deliberately designed to feel utterly annoying.

D. Procedure and Applied Measures

We conducted a user study with a mixed design. All participants were randomly split into four groups, each playing both tasks with one of the four wall designs. The study was executed in our VR lab using an HTC Vive Pro [35]. We started by informing the subjects about the study process without giving away our research focus. Subsequently, the participants completed a general questionnaire assessing gender, age, and prior VR and gaming experiences. Finally, we administered the Immersive Tendencies Questionnaire (ITQ) [36] to assess the participants' tendency to immerse in fiction.

After we introduced the participants to our VR equipment, they played the first round. Upon completion, the subjects removed the HMD and filled out the IGroup Presence Questionnaire (IPQ) [37]. We administered the IPQ to assess whether the wall designs influence the perceived presence, serving as an explanatory factor for H2. Subsequently, the subjects returned to the virtual environment to complete the second task. After finishing, the study was closed with a semistructured interview session to gather the personal reasons for ignoring or avoiding walls. Additionally, we logged the relevant playing statistics, such as the players' speed and walking distance, to confirm comparability between the two conditions. Finally, we recorded the timing and number of wall collisions. As participants might accidentally touch walls without passing them, we only counted collisions where the headset moved entirely through the wall.

IV. Results

In total, 40 persons (20 female, 20 male) participated in our study with a mean age of 24.1 ($SD = 2.68$). The subjects equally split among nonplayers, occasional players, and regular gamers, and a majority (75%) of them had already used VR headsets before. For the between-subject distinction, we randomly split the participants into four groups (A30: 11, A60: 9, RTH: 10, RWW: 10). Further, we did not find any significant differences regarding age, gender, prior VR experience, or immersive tendencies according to the ITQ (all $p > .05$).

To compare the four independent groups, we performed one-way analyses of variances (ANOVA) for the IPQ measures and most of the logged data. To meet the requirements, we ensured normal distribution with Kolmogorov-Smirnov and homogeneity of variances with Levene's tests. All measures met both conditions. This result allowed us to use Tukey's tests for all post hoc comparisons. For dichotomous data, i.e., assessing whether subjects ignored virtual walls, we used chi-squared tests of independence for comparisons between conditions and McNemar's test for comparisons between the two tasks.

A. IPQ

To determine whether our different wall designs affected the players' feeling of presence and realism, we assessed all subscales of the IPQ questionnaire. The results are depicted in Table I. For the two subdimensions involvement ($p = .022$) and realism ($p < .001$), as well as for the general feeling of presence ($p = .019$), the ANOVA indicates a significant difference. Post hoc comparisons indicate that the RTH ($p = .047$; 95% $CI[.011, 2.655]$) and RWW ($p = .029$; 95% $CI[.111, 2.755]$) conditions led to a significantly higher general presence compared to the more opaque abstract wall (A60).

Furthermore, both realistic wall designs RTH and RWW provided a significantly higher perceived realism compared to the two abstract conditions A30 and A60, according to post hoc comparisons (A30/RTH: $p = .003$; 95% $CI[.301, 1.864]$, A60/RTH: $p = .001$; 95% $CI[.966, 2.601]$, A30/RWW: $p = .016$; 95% $CI[.134, 1.689]$, A60/RWW: $p = .001$; 95% $CI[.791, 2.426]$). For the involvement subscale, only the difference between the A30 and RWW conditions is significant ($p = .027$; 95% $CI[.127, 2.787]$).

B. Logged Data

Apart from assessing the IPQ, we also analyzed the participants' play sessions by logging the individual walking trajectory, total walking distance, average walking speed, and wall collisions. The walking distance and walking speed

TABLE I

MEAN SCORES, STANDARD DEVIATIONS, AND ONE-WAY ANOVA VALUES OF THE IGROUP PRESENCE QUESTIONNAIRE (IPQ) FOR BOTH TASKS.

	A30 ($N = 11$)	A60 ($N = 9$)	RTH ($N = 10$)	RWW ($N = 10$)	F(3,36)	$\hat{\omega}^2$	p	
IPQ (scale: 0 - 6)								
Spatial Presence	4.02 (1.09)	3.91 (0.66)	4.68 (0.92)	4.90 (1.10)	2.496	.101	.075	
Involvement	3.07 (1.31)	3.33 (0.77)	4.10 (0.90)	4.53 (1.37)	3.631	.165	.022	*
Realism	3.11 (0.70)	2.42 (0.47)	4.20 (0.77)	4.03 (0.64)	15.120	.514	.001	**
General	4.27 (1.27)	3.67 (1.12)	5.00 (1.05)	5.10 (0.74)	3.766	.172	.019	*

*$p < .05$, ** $p < .01$

TABLE II

MEAN SCORES, STANDARD DEVIATIONS, AND ONE-WAY ANOVA VALUES OF THE LOGGED WALKING DISTANCES, AVERAGE WALKING SPEEDS, AND AVERAGE NUMBER OF WALL COLLISIONS FOR BOTH TASKS.

	A30 ($N = 11$)	A60 ($N = 9$)	RTH ($N = 10$)	RWW ($N = 10$)	F(3,36)	$\hat{\omega}^2$	p
Task 1: Puzzles							
Collisions	0.18 (0.40)	0.11 (0.33)	0.00 (0.00)	0.10 (0.32)	0.612	-.003	.612
Walked Distance (m)	51.75 (14.46)	49.11 (15.85)	49.20 (10.70)	53.27 (10.36)	0.240	-.060	.868
Walking Speed (m/s)	0.260 (0.052)	0.279 (0.041)	0.254 (0.021)	0.264 (0.045)	0.220	-.076	.882
Task 2: Moving Coins							
Collisions	11.91 (17.77)	20.11 (20.31)	10.80 (15.92)	6.00 (12.79)	1.136	.010	.348
Walked Distance (m)	161.58 (29.77)	172.92 (30.15)	177.23 (42.17)	184.14 (23.44)	1.589	.042	.209
Walking Speed (m/s)	0.561 (0.078)	0.536 (0.095)	0.555 (0.105)	0.545 (0.063)	0.162	-.061	.921

*$p < .05$, ** $p < .01$

measures did not reveal any significant differences between the puzzle task's four conditions. Similarly, the differences for both values were not significant for the repetitive task either. These results are depicted in Table II.

The most important data for our analysis are the participants' behavior concerning the virtual walls (see Figure 3). While playing the puzzle task, only four subjects (10%) ignored a single obstacle, whereas the others did not collide once. In contrast, 21 participants (52.5%) walked through walls in the second, repetitive task. This difference is significant according to McNemar's test ($p < .0001$). Exemplary walking trajectories of both rounds are shown in Figure 4.

When comparing the wall collisions between the four conditions for the puzzle task, we did not find any significant differences, neither between opaque and transparent walls ($\chi^2(1) = .000, p = 1.000$) nor between realistic and abstract wall designs ($\chi^2(1) = 1.111, p = .605$). However, for the repetitive task, the player behavior differs significantly between conditions of different opacity. Whereas 80% of subjects in the RWW condition avoided walking through walls, this was the case in only 36.7% of the other three groups featuring see-through walls. This difference is significant ($\chi^2(1) = 5.647, p = .028$).

On the other hand, the degree of realism had no significant influence on the behavior in the repetitive task. In the two abstract conditions A30 and A60, 60% of subjects walked through walls, whereas in the two other conditions, 45% ignored obstacles ($\chi^2(1) = .902, p = .527$). It is worth mentioning that – in contrast to the puzzle task – subjects tended to use shortcuts frequently after crossing walls once. The participants split almost exclusively into two groups: 65% of subjects collided less than four times, whereas 35% collided 23-50 times.

V. DISCUSSION

Virtual scenarios can reach their full potential, be it for entertainment or educational purposes, only if users adhere to the environment's fundamental laws. Moving through purely virtual obstacles that do not have a physical counterpart not only harms the feeling of *being there* but might also cause unwanted experiences or even result in dangerous situations. In our study, we addressed three characteristics of virtual scenarios that might foster such behavior.

H1: Repetitive and monotonous tasks provoke significantly more participants to walk through virtual walls than diverse tasks.

We approached this hypothesis by integrating two similar tasks in a within-subject design into our study. Both required the players to move virtual items between interaction points spread across the play area. The necessary completion time and walking distance were chosen similarly so that the task's motivation remained the only variation. The significant difference between both tasks regarding players that cut short through walls, i.e., 10% versus 52.5%, confirms our hypothesis.

Furthermore, we observed that all subjects, who walked through walls in the diverse puzzle task, tried this shortcut only once. In contrast, 35% of the participants ignored most of the walls in the repetitive condition. This finding further supports our initial assumption that player behavior mainly relies on personal interest in the situation. Varying and interesting assignments preserve the scenario's plausibility and provide a solid incentive to stick to the rules. On the other hand, repeated and simple actions fail to keep the players immersed in the virtual world. As oral feedback suggests, participants were more aware of the real situation and looked forward to

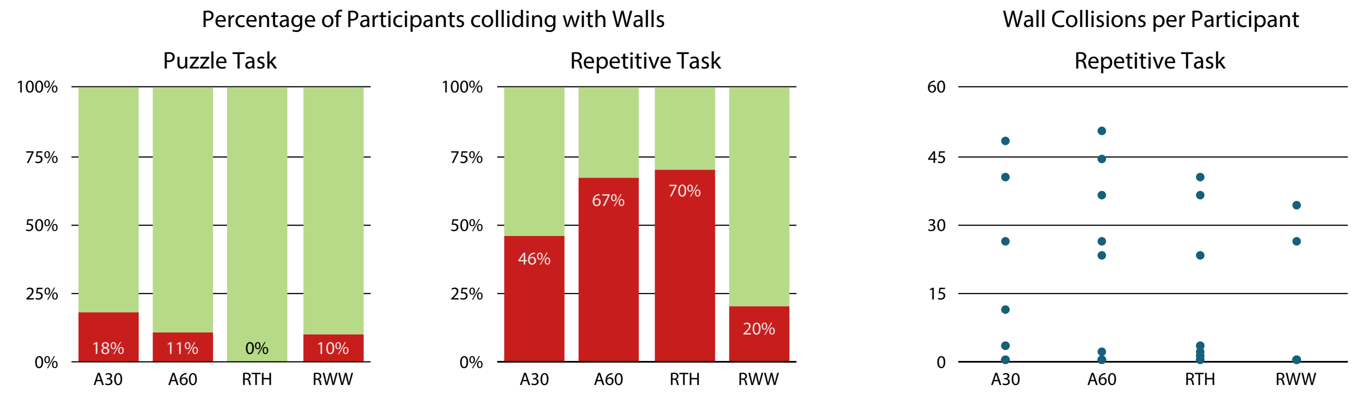

Fig. 3. Results from the data logged during the play sessions. Left: the percentage of subjects walking through at least one wall for each task and condition. Right: dot-plot of the wall collisions per participant and condition in the repetitive task.

completing the task: *"I knew that the walls were not real, so I just walked through them to get this annoying task done as fast as possible."(**P14**).*

H2: Participants walk significantly more often through abstract walls than through realistic walls.

Among the four walls that we tested in a between-subject design, two were implemented as abstract blocks (A30 & A60), and the other two thematically fit the testbed scenario (RTH & RWW). We assumed designs that matched less would serve as a *break-in-presence* [9], diminishing the visual realism and consequently leading to less conform behavior. By administering the IPQ, we confirmed that the abstract walls indeed harmed the perceived presence and realism. Additionally, subjects later reported that the walls in these conditions *"felt like unfinished placeholders and somewhat ruined the appealing visuals of the scenery"(**P2**).*

However, these observations did not affect the participants' walking behavior. Even though the percentage of subjects walking through walls was tendentially higher for the abstract conditions (in the repetitive task: 56.1% versus 45%), this difference was not significant. Therefore, we cannot confirm our second hypothesis. Considering the observed tendencies in the data, we suspect the potential presence of a less noticeable effect that was overlain by the strong findings of H1 and H3. Thus, we propose further research to investigate this open question in isolation.

H3: Opaque surfaces deter more participants from ignoring virtual obstacles than partly transparent surfaces.

Apart from varying the virtual walls in the degree of realism, we also used multiple opacity levels. For this hypothesis, we group A30, A60, and RTH into one category of see-through designs. Even though the twine material was fully opaque, the underlying wall model featured numerous holes, clearly revealing the other side. In contrast to these designs, the wooden surface completely blocked the view of objects behind the wall. This differentiation between conditions resulted in significantly different behavior observed in the repetitive task: 63.3% of the subjects in the see-through conditions deliberately ignored walls, compared to only 20% in the RWW condition.

Subjects often reported the wall's transparency as assuring factor in their decision-making: *"I saw that my goal was right behind the wall. Since I knew that there were no free-standing walls in the room, I felt safe to walk through."(**P8**).* Similarly, participants in the RWW group felt deterred by the solid appearance of the wall: *"Of course I knew that these walls were only virtual. But they appeared so sturdy that I preferred to walk around."(**P11**).* The oral feedback shows that users generally prefer the safety of seeing where they are going and refrain from walking into unclear areas. Together with the recorded data, this finding confirms our hypothesis that opaque surfaces deter players from walking through walls.

RQ1: How do players decide whether they pass through virtual walls or walk around them?

Apart from investigating our three main hypotheses, we were also interested in the participants' reasons for deciding whether they walk through or around virtual walls. Thus, we followed the main study with a semistructured interview allowing the subjects to share their personal thoughts. We analyzed the resulting interview data for reoccurring motives using a peer-reviewed deductive thematic analysis [38] and structured the reasons into two categories.

A. Reasons for refraining from walking through obstacles

The overwhelming majority of subjects stated a simple reason for not even considering walking through obviously virtual walls: *"Walls are solid, you cannot walk through them."(**P3**).* This feedback indicates a strong *Plausibility Illusion*. The participants transferred the real world's fundamental rules to the virtual scenario and stuck to basic physical principles, treating the virtual environment like its material counterpart.

Many subjects also reported their fear of negative consequences when breaking the rules. This reason encloses a variety of partly subconscious considerations. Some participants felt unsure not being able to see behind the wall: *"I would not have seen what was directly in front of me, so I decided to stay* *cautious."(**P16**)*. Others feared hurting themselves: *"The twines seemed painful – I usually avoid touching such hedges."(**P23**)*. Finally, subjects also expected to get punished for nonadherent behavior, such as *"having to restart the level"(**P20**)*.

B. Reasons for walking through obstacles

The most commonly mentioned reason for ignoring the walls in the puzzle task was curiosity. Participants were eager to explore their abilities in the virtual world and test the game's rules. However, after experiencing the absence of any punishment, all subjects reverted to an adherent playstyle for the remaining time: *"It was interesting to revolt against the intended playstyle. But after trying once, I decided that walking around the walls was more fun and felt more natural."(**P1**)*.

For the repetitive task, most players reported a different reason for their behavior: cutting short. As this round consisted only of the always same interaction of putting coins on matching plates, subjects mostly decided to act pragmatically and *"choose the shorted possible path, even though walking through the walls felt awkward and unnatural"(**P19**)*. The logged walking trajectories support this feedback as many participants began walking as intended and only started cutting short after realizing that the task would not change for the remainder of the round.

Finally, few subjects in the more transparent A30 condition mentioned a different reason not observed for any other group. These players did not recognize the walls as obstacles being part of the virtual environment. Instead, they had the impression that *"these vitreous-looking cuboids must have been some kind of graphical artifact that had no particular meaning. It did not match the underwater scenario and was barely visible, so I thought it was safe to ignore."(**P26**)*. This feedback is in line with findings by Simeone et al. [4], who reported that incorrect interpretations could lead to arbitrary behavior.

VI. Conclusion and Future Work

When playing VR games, users might not always behave in the intended way or adhere to the fundamental principles of virtual scenarios. While developers can prevent most of such behavior through prescient game design, some challenges remain. One prominent example is the discrepancy between the physical surroundings and the virtual world. When using real walking, players can walk freely within the play area's boundaries, despite virtual obstacles blocking their path. It is not possible to prohibit such behavior without losing the valuable advantages of natural walking. Therefore, past research has mainly concentrated on providing multisensory collision feedback to deter players from deliberately walking through virtual walls. However, it remained unclear how the virtual scenarios' characteristics, such as wall design or task type, influence the players' incentives toward this behavior.

In our work, we investigated how players reacted when confronted with different situations. We thus concentrated on three potentially influencing factors: task type, wall opacity, and wall realism. In a mixed study, we confronted the subjects with two iterations of item-carry tasks. One round featured an

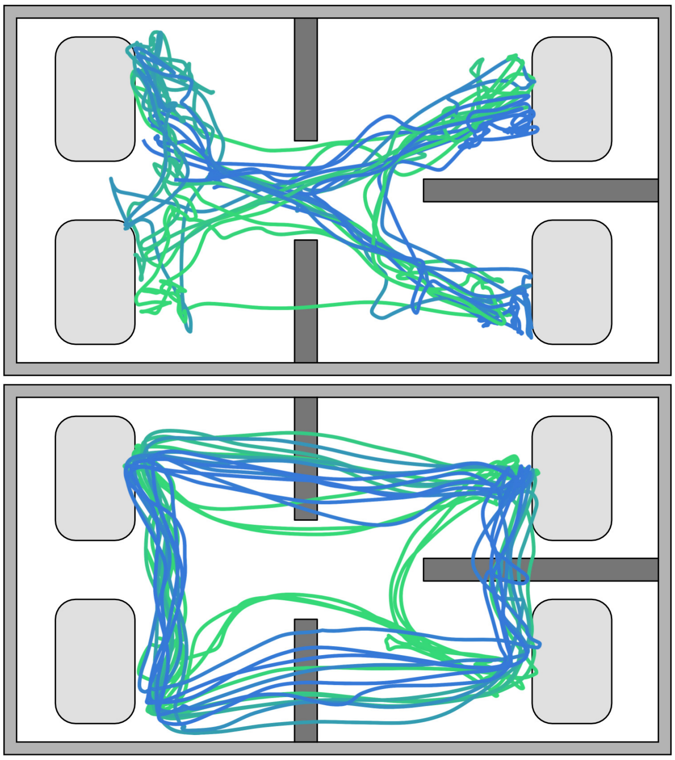

Fig. 4. Two exemplary walking trajectories of our study. The path's color changes from blue to green. Top: subject solving the riddle task and colliding once with a wall. Bottom: subject playing the repetitive task and ignoring the virtual walls most of the time.

engaging motivation, whereas the other lacked any interesting variety and focussed on repetition only. Participants in the repetitive condition cut short significantly more often to finish the assignment as fast as possible. Further, we varied the tested wall layouts in a between-subject design to cover different degrees of realism and opacity. Even though significantly more subjects ignored transparent walls than solid ones, we could not find a similar difference between realistic and abstract designs.

Our findings reveal that various factors influence the individual decision whether players adhere to or ignore obstacles in the virtual scenario. One of the most decisive parameters is the task type. Challenges that keep the players engaged and interested in the experience are particularly effective in avoiding nonadherent behavior. In contrast, repetitions, simple interactions, or forced obligatory tasks diminish the users' feeling of presence and foster pragmatic actions. In such cases, opaque surfaces deter more players from walking through virtual walls as these hide the destination and cause doubts regarding the penetrability. These findings extend the existing research corpus on player behavior and help developers design virtual scenarios that reach their full potential.

Future studies are needed to investigate the open questions on player behavior in the context of virtual collisions. Even though we did not find any evidence for an influence of the degree of realism, we suspect that our other findings might have concealed a potential minor effect. Apart from this lack of clarity, we also aim to research whether the observed behavior might be affected by individual player characteristics. Throughout the study, we noticed that participants either walked strictly around every wall or always took the direct path. However, we did not arrive at a final explanation for this almost binary classification. Finally, how time pressure might alter the observed behavior remains to be investigated. Strictly timed tasks were often used by prior research to provide a strong wall-ignoring incentive. However, this approach was based upon personal experiences and has not yet been observed in isolation.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	**Towards Sneaking as a Playful Input Modality for Virtual Environments** *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put…": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Towards Sneaking as a Playful Input Modality for Virtual Environments

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2021 IEEE Virtual Reality and 3D User Interfaces (VR)

Towards Sneaking as a Playful Input Modality for Virtual Environments

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Figure 1: We explore the potential of sneaking as a novel input modality for immersive virtual environments. In addition to hiding visually, players also must pay attention to their own gait to avoid detection.

Abstract

Using virtual reality setups, users can fade out of their surroundings and dive fully into a thrilling and appealing virtual environment. The success of such immersive experiences depends heavily on natural and engaging interactions with the virtual world. As developers tend to focus on intuitive hand controls, other aspects of the broad range of full-body capabilities are easily left vacant. One repeatedly overlooked input modality is the user's gait. Even though users may walk physically to explore the environment, it usually does not matter how they move. However, gait-based interactions, using the variety of information contained in human gait, could offer interesting benefits for immersive experiences. For instance, stealth VR-games could profit from this additional range of interaction fidelity in the form of a sneaking-based input modality.

In our work, we explore the potential of sneaking as a playful input modality for virtual environments. Therefore, we discuss possible sneaking-based gameplay mechanisms and develop three technical approaches, including precise foot-tracking and two abstraction levels. Our evaluation reveals the potential of sneaking-based interactions in IVEs, offering unique challenges and thrilling gameplay. For these interactions, precise tracking of individual footsteps is unnecessary, as a more abstract approach focusing on the players' intention offers the same experience while providing better comprehensible feedback. Based on these findings, we discuss the broader potential and individual strengths of our gait-centered interactions.

Index Terms: Human-centered computing—Virtual reality; Software and its engineering—Interactive games

1 Introduction

Imagine being a spy infiltrating a secret base, sneaking past patrolling guards, stealing the confidential information, and leaving — unseen. This plot reads like a typical mission of any stealth game. While such games already deliver an intense experience when consumed on a flat-screen, virtual reality (VR) setups provide the unique potential of boosting tension and involvement even further. Players may fully dive into the character's role and experience the plot themselves. Nevertheless, existing stealth VR-games often fail to reach this enormous potential. Most of the available titles, such as Espire 1: VR Operative [12], do not offer a fully fetched sneaking mechanism. Instead, players have to use virtual locomotion techniques and activate a binary sneak mode using hardware buttons. While enemies may visually detect the players, one of the central aspects of sneaking is left vacant: being quiet.

In the real world, every step we take emits noise. Apart from revealing our position and speed, these walking sounds also expose a broad range of personal information, including gender [36], emo-

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tional state [15], or posture [43]. Still, we usually tend to ignore them in our everyday life. Things change when the situation requires secrecy and discretion. Sneaking needs both – staying out of sight and adopting the own gait to minimize walking sounds. On the other hand, one can also attract attention by producing sounds intentionally, i.e., through stomping. This range of interaction fidelity, which is still missing in today's VR games, could greatly benefit immersive VR experiences.

Our research closes this gap by assessing the potential of sneaking as a novel input modality for immersive virtual environments (IVEs). Therefore, we split our work into three consecutive parts: We start by developing the technical basis for capturing the users' sneaking behavior. In this process, we provide insights into our exploratory design process that covered a range of different technical approaches, e.g., using microphones or marker-based tracking, as well as various abstraction levels. We also discuss the reasoning behind our final selection of three fundamentally different implementations.

In the second part of this work, we develop possible interactions and gameplay elements utilizing our stealth mechanisms. Combining sneaking with other time- or body-based tasks allows us to modify the overall task difficulty and provide varied challenges. In the final step, we compare our three sneaking mechanisms in a between-subject study, using the developed interaction concepts. Our context is an immersive stealth VR-game, where the subjects take the role of a secret agent, stealing confidential information (see Figure 1).

Our results reveal the great potential of sneaking as an input modality for IVEs, providing high presence and enjoyment levels. The body-based mechanisms offer unique challenges and thrilling gameplay. Comparing the different technical approaches, we found that precise tracking of individual footsteps is unnecessary for the particular use-case. Instead, a more abstract approach focusing on the players' intention offers the same experience while providing better comprehensible feedback. In turn, accurate footstep tracking could be used for a variety of other use-cases, e.g., for training simulations providing individual gait-related feedback. These findings form the basis for further research on other gait-related interaction concepts.

2 Related Work

In this section, we cover the related research relevant to this work. We start by briefly covering the basic concepts linked to playing games in VR — immersion, presence, and cybersickness. Next, we provide a concise summary of VR locomotion research, as our topic is closely linked to this area. Lastly, we discuss the latest advancements enriching IVEs with novel sensations or a greater input fidelity, focusing primarily on gait-related approaches.

Modern head-mounted displays (HMDs), such as the Oculus Quest 2 [13], replace the users' real surroundings with a realistic representation of the virtual world. In this context, researchers usually call the technical quality of the used hardware *immersion* [5, 8, 50] and the perceptual effect of being in the IVE *presence* [18, 51]. The latter is of particular interest for this work and can be measured using various approaches [10, 24, 37]. Apart from the positive experience of diving into a fully immersive environment, VR also bears the risk of causing cybersickness [19, 35]. In this case, a mismatch between the human vision and the vestibular system causes symptoms ranging from headaches to vomiting.

Especially poorly suited locomotion techniques bear the risk of quickly inducing high levels of discomfort [16]. Thus, recent work has mostly focused on using natural locomotion approaches, such as real walking [47], to counter this threat. These efforts center around the concept of extending the walking range by augmenting real movements [4, 7, 26], changing perspectives [2, 9, 32], or subconsciously avoiding real obstacles [46]. Among these approaches, the *walking-in-place* concept is of particular interest as it derives the users' anticipated motion from in-place steps [52]. While being superior to gamepad locomotion, early implementations did not feel as natural as real walking [61]. Thus, later research [14, 56, 68] has focused on improving the matching, e.g., by using the biomechanics of human gait [65]. Since our work connects only loosely to VR locomotion research, we point to Boletsis et al. [6] and Krekhov et al. [34] for a more detailed overview of the current state of the art.

Recently, a particular focus in VR research has been placed on enhancing the users' perception of the virtual world. These efforts mostly focus on adding additional sensations exceeding the visual and audio components of currently available headsets. Examples include haptic surface feedback [66], weight-shifting controllers [69], or olfactory systems [40]. Instead of adding novel sensations, other projects used the existing capabilities to manipulate the users' impression of the virtual world. In this context, a special focus was placed on the effects of displaying virtual avatars in various shapes and appearances [38]. For instance, altering the users' avatar can not only evoke the impression of changing age [3], race [30, 44], or even species [33] but also impact mental health, like in the case of eating disorders [45]. Specifically related to our particular research interest, Pan and Steed [42] focused on the influence of virtual legs and feet on presence and embodiment.

Apart from enriching the users' interactions and sensations in general, a growing body of research has focused on improving the movement through virtual scenarios. A compelling and realistic walking experience requires a profound knowledge of the biomechanical fundamentals of human gait. The upright bipedal progression characterizing human locomotion is commonly defined as a periodic movement of the two lower limbs. The underlying pattern, i.e., the *gait cycle* [25], consists of two phases: the swing phase, where the foot is in the air, and the stance phase, where the foot has contact with the ground [29]. The latter phase is subdivided into four stages [23, 39]: heel strike, forefoot contact, midstance, and heel off. The interplay of alternating swing and stance phases leads to forward propulsion. Individual differences, such as gender, age, posture, or walking speed, significantly influence the particular gait [31, 58], and it was shown that listeners could deduce these characteristics solely from the emitted walking sounds [63]. Also, research mainly differentiates between two primary types of gait: walking and running [11, 21]. Apart from the velocity, the main difference is the flight phase while running, i.e., no foot is touching the ground. Thus, we consider sneaking a subtype of walking, characterized by a more careful foot placement.

In the last decades, foot-based interactions have been of ongoing interest to the research community [62]. For virtual scenarios, most of the work has focused on more realistic walking experiences. The *Real-Walk* approach by Son et al. [53] simulates various surfaces by altering the viscosity of a shoe-like apparatus. Similarly, King et al. [57] combined visual with tactile vibrations to improve the realism of walking in VR. Strohmeier et al. [54] presented their *bARefoot* prototype capable of generating virtual walking surfaces through motion-coupled vibrations. Our work — exploring sneaking as an input modality — adds to the research dealing with the auditive aspect of walking. This research area is mostly centered around synthesizing or modifying the users' footstep sounds as part of the overall soundscape. For instance, Tajadura et al. [55] showed that modified walking sounds alter the self-perception. Also, Kern et al. [28] reported the positive effects of synchronized step sounds on presence and realism. For a broader view on the interplay between synthesized footstep sounds and immersive soundscapes, we point to the extensive work by the Medialogy Department at Aalborg University Copenhagen [41, 49, 59]. The closest related work in this field is the *VRSneaky* approach by Hoppe et al. [20]. The authors use shoe-attached trackers to play gait-aware walking sounds in a stealthy IVE to provoke a gait-change and achieve an increased presence. While these works underline the importance of plausible soundscapes, including synchronized walking sounds, our work concentrates on the potential of the users' sneaking behavior as a novel input modality.

3 Developing the Sneaking Mechanisms

While past research has already dealt with capturing the users' walking behavior and using this information in virtual environments, these approaches mainly aimed to achieve a realistic soundscape. In contrast, our mechanism should translate the users' gait into a discrete state, i.e., differentiating between walking and sneaking. This processed information would form the basis for our novel input modality. From the very start of our design process, we decided to start from scratch and refrain from using any auditory walking feedback with our mechanism. Existing research, such as VRSneaky [20], have already demonstrated the benefits of precisely synchronized footstep sounds for presence and gait awareness. We wanted to focus entirely on the interactional aspect and determine the necessary tracking fidelity needed for a plausible sneaking mechanism.

Based on this goal, we determined three main requirements for the target implementation. Firstly, the mechanism must be able to differentiate between the two states *walking* and *sneaking*. We do not distinguish between walking and stomping, as both share the same source, i.e., stepping with normal force, and the same effect, i.e., attracting attention. Secondly, the used tracking mechanism must deliver robust signals to determine the active state independent of the users' physiologies, walking behavior, and other environmental factors, i.e., ground, footwear, or noise. Finally, the chosen tracking method must not impede the users' movement in the real world in any way. This constraint also applies to hardware that might alter or diminish the fine-graded foot movement necessary for sneaking.

Considering these prerequisites, we started by capturing the real step sounds emitted by the users. Therefore, we attached Bluetooth microphones to the users' ankles and used the transmitted audio volume to extract the users' gait. This approach is the exact realization of the abstract idea behind our work. The lightweight microphones guarantee an easy setup that is not intervening with the actual gameplay. However, external interferences and individual differences between users are only partially removable by filtering. Eager to find a better alternative, we experimented with various other approaches. In particular, we shifted our focus from measuring the exact sounds to detecting the foot motions during sneaking.

Compared to other alternatives, such as force-sensing resistors, our final implementation uses the existent precise VR tracking environment and only requires a pair of HTC Vive trackers attached to the users' feet. This setup does not influence the individual sneaking movement and provides seamless and quick integration with the overall VR system. As with every sensor device, minor tracking errors and inaccuracies might occur from time to time. Also, using the trackers' exact positions to determine the foot's touchdown would require precise calibration as every users' feet are different. However, we found that these issues are avoidable by rethinking the definition of silent footsteps. When a foot is placed on the floor, the ground slows its speed to zero. The faster a foot is slammed down, the more noise is produced. Thus, the step sounds are directly dependent on the decrease in velocity.

Plotting the decrease in velocity over time reveals the users' gait. Note that we isolate the deceleration alone:

$$d(v,t) = \begin{cases} \frac{\Delta v}{\Delta t} & \text{if } \Delta v \leq 0 \\ 0 & \text{otherwise} \end{cases}$$

The resulting peaks correspond to when the users place their foot on the floor. These measured values vary only minimally across different users, making it possible to determine global thresholds for different types of gait (see Figure 2). While this approach is immune to typical noise sources, such as random foot movements or physiological differences, we noticed that minor tracking errors might still trigger an unexpected peak. We solved this impediment by adding a small sliding window to eliminate single erroneous frames. After all, this tracker-based approach has a minimal impact on the movement and provides a reliable and precise tracking of the users' gait.

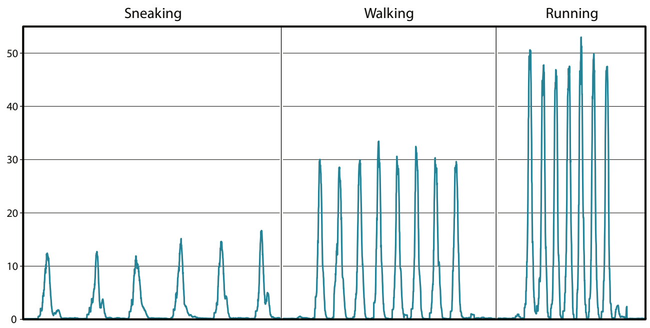

Figure 2: Plotted deceleration values (in m/s^2) for a typical player. The average peaks for sneaking, walking, and running activities (from left to right) vary only minimally across different users, providing robust thresholds for the different types of gait.

During the design process of our first implementation, we learned that it might be beneficial to use a more abstract approach instead of measuring walking sounds directly. The result stays the same: we can detect whether users are walking or sneaking. Next, we asked ourselves: Do we even need to track individual steps? When testing our early prototypes, all test users shared one similarity when sneaking: they walked slowly. While it would certainly be possible to sneak quietly without sacrificing much of the original walking speed, we usually measured a significant decrease in general velocity during our trials. It seems that this observation is tightly associated with the users' expectations. Thus, we designed our second approach to measure the overall walking speed using the horizontal velocity of the HMD. The threshold, determining whether users sneak or walk, was chosen based on the tracking data of our pre-tests. Like the first tracker-based mechanism, we added a sliding window to account for tracking issues and the head's micro-movements. Apart from that, both approaches work almost identical.

The main difference between our two implementations is the loss of tracking fidelity. Only the first technique can detect the actual gait, whereas the second mechanism relies on an implicit observation. Nonetheless, both approaches are body-based interactions and are compatible with natural walking, which is generally seen as the best locomotion technique for virtual environments [61]. In contrast, existing stealth VR-games are geared to sneaking mechanisms of established non-VR games. These games tend to use a binary stealth mode that is triggered using a hardware button. Players are slowed down and become harder to detect by the NPCs. Of course, this approach requires a virtual locomotion technique to control the player's position and movement. While not entirely comparable to our walking-oriented mechanisms, we decided to add gamepad-based sneaking as a third baseline implementation. This approach uses a continuous joystick movement and introduces a dedicated button triggering the sneaking mode. While sneaking, users are limited to a lower velocity that does not attract attention. It is worth noting that this mode is optional, as users might use the joystick carefully enough to achieve the same effect.

Altogether, our design and implementation phase leaves us with three different approaches to detect sneaking:

- *Tracker*: ankle-attached trackers measure the foot's deceleration
- *HMD*: HMD's movement is used as a proxy for the users' speed
- *Gamepad*: joystick locomotion and button-controlled sneak mode

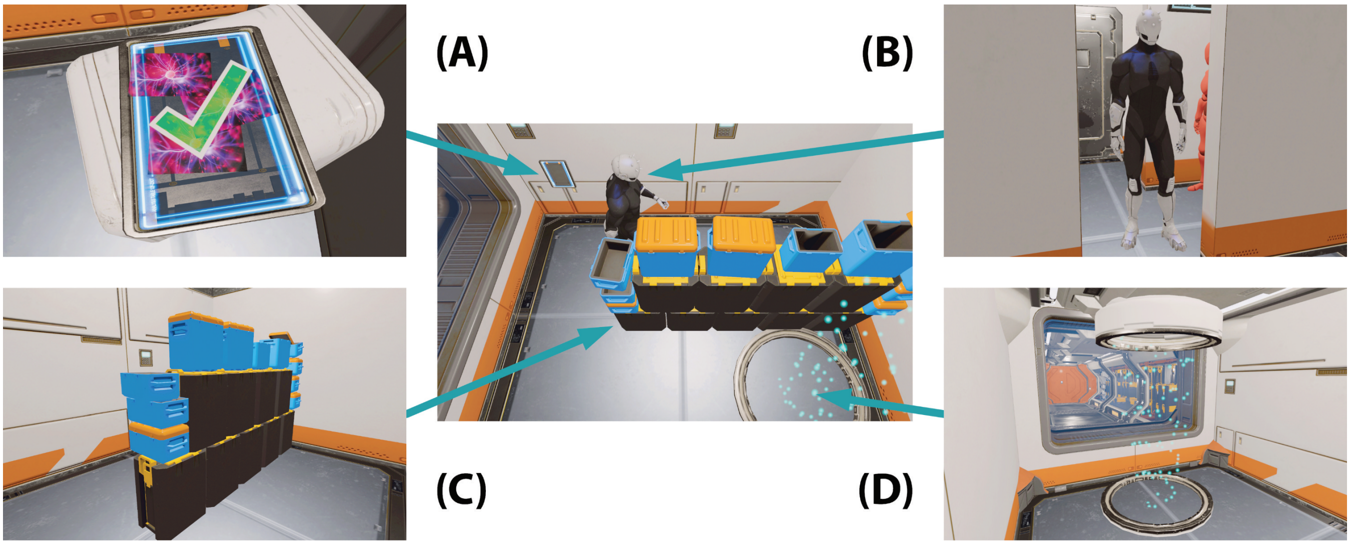

Figure 3: Overview of a typical level of our testbed game, including all important elements: the target tablet (A), the enemy guard (B), obstacles providing cover (C), and the teleporter serving as entry and exit (D).

4 Designing Sneaking-based Interactions

Apart from developing the technical basis for measuring the users' gait, it is crucial to design gameplay elements and interactions that utilize the novel input channel. On the surface, our sneaking mechanism appears to be a simple binary differentiation: If the players walk carefully enough, everything is fine. Otherwise, they are detected.

In this regard, sneaking is very similar to hiding visually from enemies. Both mechanisms build on top of the normal locomotion in the virtual scenario. However, they differ in the underlying challenge. Hiding behind obstacles and avoiding a direct line of sight is a complex body-based task. Players must pay attention to the positioning of all body parts, i.e., not letting a limb peek out of the coverage. On the other hand, sneaking does not constrain the players' position but requires careful movement. Thus, hiding is challenging the *where to move* and sneaking the *how to move*. Both mechanisms are often used in conjunction to increase the overall difficulty.

Besides this famous coalescence, sneaking might be combined with other interaction patterns to obtain interesting challenges and vary the degree of difficulty. We subdivide these patterns into two groups: *reinforcing* and *contradicting* elements. A task is called *reinforcing* if it intensifies the players' attention on their movement. Typical examples include stepping over obstacles or crouching behind barriers. These tasks add an additional movement challenge forcing the players to focus even more on every step. Conversely, *contradicting* gameplay elements split the players' attention between the newly emerged challenge and the active sneaking task. For instance, getting past patrolling guards requires spatial understanding and precise timing, while players still must avoid getting heard.

Finally, the switch between quiet sneaking and loud walking itself is another potential gameplay element. A common feature found in almost every stealth game is the capability of producing sound on purpose. Whistling or stomping may attract attention and lure enemies to desired spots. In essence, this interaction combines the known gameplay elements. Stomping is another type of *reinforcing* action, as it requires stopping sneaking for one single step. Next follows a typical *contradicting* time-based task, e.g., guards investigating the noise's source. Thus, we consider such composite features to be more complex than their primary counterparts.

Table 1: Gameplay overview of our testbed stealth game. In each of the ten consecutive levels, we add one additional gameplay concept.

Level	Description	Gameplay Concept
01	guard is outside of the room	steal the tablet
02	guard is outside, tablet is hidden	search the tablet
03	guard is facing the wall	sneak
04	guard is observing the obvious path	avoid the guard's sight
05	guard is turning regularly	time the own movements
06	guard patrols along a fixed path	analyze the patrol
07	guard patrols through the entire room	keep moving
08	dynamic obstacles provide cover	combine multiple timings
09	lasers block the path at breast height	crouch past obstacles
10	guard stands behind a counter	move while crouching

5 Evaluation

We conducted a study to evaluate our three proposed sneaking techniques using a between-subject design. We were primarily interested in the general acceptance of our mechanisms and the differences in enjoyment, presence, tension, difficulty, and necessary effort. Therefore, we designed a VR stealth game that consisted of multiple short levels, each focusing on one of the introduced interactions.

5.1 Research Questions and Hypotheses

The study's main goal is to explore the differences between the three implementations Tracker, HMD, and Gamepad. In this context, we refer to both of our two proposed approaches, HMD and Tracker, as full-body movement-based interactions. We hypothesize that these techniques, resembling real sneaking, benefit the perceived presence. Additionally, such gait-based interactions force the players to pay attention to every step they take. Consequently, we expect a significantly higher physical effort compared to the Gamepad controls. Also, we assume an overall increase in task complexity. Despite these difficulties, we do not expect a lower success rate. Instead, the novel challenges are likely to increase the players' tension and enjoyment. All in all, our hypotheses are as following:

Table 2: Mean scores, standard deviations, and one-way ANOVA values of the Presence Questionnaire (PQ), the Intrinsic Motivation Inventory (IMI), the Player Experience Inventory (PXI), the NASA Task Load Index (NASA-TLX), and the Simulator Sickness Questionnaire (SSQ).

	Tracker ($N = 15$)	HMD ($N = 15$)	Gamepad ($N = 15$)	F(2,42)	η^2	p	
PQ (scale: 0 - 6)							
Realism	4.98 (0.63)	5.03 (0.68)	4.02 (0.91)	8.695	0.293	.001	**
Possibility to Act	4.92 (0.71)	4.78 (0.55)	4.83 (0.69)	0.161	0.008	.852	
Interface Quality	5.16 (1.13)	5.02 (1.16)	5.18 (0.64)	0.106	0.005	.900	
Possibility to Examine	4.89 (0.88)	4.80 (0.81)	4.47 (0.96)	0.947	0.043	.396	
Performance	4.90 (0.76)	4.70 (1.11)	4.57 (1.02)	0.444	0.021	.644	
Total	4.97 (0.52)	4.98 (0.56)	4.46 (0.66)	3.897	0.157	.028	*
IMI (scale: 0 - 6)							
Interest/Enjoyment	5.37 (0.46)	5.20 (0.76)	5.15 (0.53)	0.557	0.026	.577	
Pressure/Tension	3.07 (0.73)	2.85 (0.59)	2.27 (0.64)	5.985	0.185	.005	**
PXI (scale: 0 - 6)							
Challenge	5.11 (0.85)	4.98 (0.90)	3.73 (1.18)	8.929	0.000	.001	**
NASA-TLX (scale: 0 - 99)							
Physical Demand	65.00 (15.81)	36.00 (23.92)	25.00 (17.428)	17.069	0.448	.000	**
Mental Demand	53.33 (24.62)	45.00 (25.00)	46.33 (21.08)	0.538	0.025	.588	
SSQ (scale: 0 - 3)							
Nausea	24.80 (23.31)	9.54 (13.00)	41.98 (46.71)	5.007	0.163	.015	*
Oculomotor	20.21 (22.68)	13.82 (9.92)	33.37 (29.35)	3.137	0.126	.062	
Disorientation	22.27 (24.57)	7.42 (12.74)	44.54 (46.53)	5.770	0.203	.009	*

$*p < .05$, $**\ p < .01$

- H1: In comparison to the Gamepad condition, the Tracker and HMD approaches **significantly increase the perceived presence**.
- H2: The full-body conditions require a **significantly higher physical effort** compared to the Gamepad controls.
- H3: The Tracker and HMD conditions **significantly increase task difficulty but not the success rate**.
- H4: Movement-based sneaking **significantly boosts players' enjoyment and tension** compared to the Gamepad approach.

Apart from these four hypotheses, we are also interested in how the players perceive the different sneaking techniques: Are the controls easy to learn and usable? How do the techniques compare to real sneaking? Finally, we want to use the insights from the hypotheses, logged gameplay data, and participants' feedback to compare our two proposed approaches against each other. We summarize both aspects into two additional research questions:

- RQ1: How do players assess their particular sneaking technique regarding usability, learnability, and realism?
- RQ2: Are there notable differences between the two proposed walking-based approaches HMD and Tracker?

5.2 Scenario

We realized the stealth game, used for comparing the different sneaking techniques, with the Unity game engine [60]. The setting is futuristic and highly technological, including teleports and patrolling robots (see Figure 3). The players take the role of a spy who must steal a tablet with confidential information hidden somewhere in the level. Since two of our sneaking mechanisms rely on natural walking, we restricted the virtual environment's size to match our real play area's boundaries, i.e., $16m^2$. Each of the ten consecutive levels is structured similarly: The players enter the room using a teleporter, which serves as a loading screen. While obstacles, e.g., crates, walls, or laser barriers, differ each time, at least two elements are found in every level: the target tablet and a sentinel robot.

This guard is the main antagonist in the game. If players fail to sneak while walking through the level, they attract attention to their position, causing the robot to investigate the noise's source. If the robot detects the players visually, a bar indicating the alertness level begins to fill. Similar to other games, only the HMD's position is used to determine visibility. Players who fail to interrupt the robot's line of sight will be caught and must restart the level. Therefore, players must do their best to stay unseen and unheard. In the case of detection, the environment offers various corners and blinds that help the players hide and wait for the guard to stop searching. Additionally, we provide a holographic noise indicator attached to the hand, informing the players whether they are sneaking quietly enough. As only one condition involves positional foot tracking, we refrain from visualizing feet or body to assure comparability. Also, prior research already covered the effects of displaying virtual limbs [42].

While walking through the level and locating the tablet, the players have to overcome various challenges and obstacles. These are designed carefully to introduce new gameplay concepts one at a time. In the beginning, players only need to sneak to avoid the guard, who is looking out of a window. Subsequently, we add the guard's lookout, time-based patrols, dynamic obstacles, and crouching activities. A complete list of the mechanisms used in each of the ten levels is depicted in Table 1. After retrieving the tablet, the players must return quietly to their starting point. They are then teleported back to a waiting room where they start the next level.

5.3 Procedure and Applied Measures

We conducted a between-subject study splitting the participants randomly into three groups, each using one of the proposed sneaking techniques. In the beginning, we considered a within-subject design to collect qualitative feedback comparing the different implementations. However, the necessary repetition of gameplay elements paired with the general similarity between the sneaking approaches would have led to unwanted sequence effects.

We executed the study in our VR lab using an HTC Vive Pro Wireless setup [22]. On average, the study took 45 minutes. At first, the participants were informed about the overall process and completed a general questionnaire assessing gender, age, gaming behavior, and prior VR experience. We also administered the Immersive Tendencies Questionnaire (ITQ) [67] to determine the ability to get immersed in fiction. At last, we introduced the participants to the VR hardware and assisted them in putting on the hardware.

The participants started the game in a waiting room, where they were introduced to the controls needed to complete the levels. While there was no guard present in the waiting room, the subjects could

Table 3: Mean scores, standard deviations, and one-way ANOVA values of the custom questions (CQ).

Question Item		Tracker	HMD	Gamepad	F(2,42)	η^2	p	
CQ1	The sneaking felt realistic.	5.20 (1.01)	4.53 (1.30)	3.67 (1.50)	5.361	0.203	.008	**
CQ2	The sneaking did not feel right.	1.80 (2.04)	1.93 (2.15)	1.60 (1.55)	0.113	0.005	.893	
CQ3	The sneaking technique was intuitive.	4.67 (1.50)	4.67 (1.18)	5.60 (0.63)	3.251	0.134	.049	*
CQ4	I had to make an effort to sneak.	4.20 (1.47)	3.07 (1.62)	1.00 (0.93)	27.759	0.499	.000	**
CQ5	The sneaking was too difficult.	2.00 (1.69)	1.27 (1.16)	0.20 (0.41)	12.257	0.286	.000	**
CQ6	I felt very active while playing.	5.33 (0.72)	5.00 (0.85)	3.73 (1.91)	25.886	0.238	.019	**
CQ7	I would have preferred another sneaking technique.	1.80 (1.78)	0.73 (1.22)	1.80 (1.52)	2.445	0.104	.099	
CQ8	I would have liked to play more levels.	5.27 (1.33)	5.07 (0.88)	4.53 (2.10)	0.928	0.042	.403	
CQ9	I would like to play more sneaking-based VR games in the future.	5.13 (1.25)	4.87 (1.36)	4.20 (1.42)	2.026	0.088	.145	

*$p < .05$, ** $p < .01$

use their holographic noise indicator to test the particular sneaking technique. We did not limit this introductory phase, which usually only took one to two minutes. After getting used to the controls, the subjects entered the first level by stepping on the teleporting device and returned to the waiting room between every level. We logged the relevant statistics, such as the overall playtime or the number of detections, to analyze the players' performance.

After completing the final level, the subjects removed the HMD and filled out a series of questionnaires regarding their experience. For administering the feeling of presence, we used the Presence Questionnaire (PQ) [10, 67] focussing on interaction-related presence. It contains five subdimensions, each rated on a 7-point Likert scale (coded 0 - 6): *realism*, *possibility to act*, *quality of interface*, *possibility to examine*, and *self-evaluation of performance*. We also included the *challenge* construct of the Player Experience Inventory (PXI) [1] and two subscales of the Intrinsic Motivation Inventory (IMI) [48]: *interest/enjoyment* and *pressure/tension* (coded 0 - 6).

For assessing the mental and physical effort, we used the NASA Task Load Index (NASA-TLX) questionnaire [17]. The two chosen subscales *mental demand* and *physical demand* are rated on a 100-point scale with 5-point steps (coded 0-99). Finally, we also included the Simulator Sickness Questionnaire (SSQ) [27] with its three subscales *nausea*, *oculumotor*, and *disorientation*. While we expected to find certain differences in cybersickness, these should relate to the different locomotion techniques, i.e., walking and gamepad, and not to the sneaking mechanism itself. The questionnaires were accompanied by a set of custom questions (coded 0 - 6) to gain further insights into the participants' experiences with the sneaking mechanisms (see Table 3). We finished the study by allowing the subjects to share their opinions in a semi-structured interview.

6 Results

In total, 45 persons (19 female, 26 male) participated in our study with a mean age of 24.64 (SD=3.13). Most of the subjects played digital games a few times a month (93%) and had already used VR systems before (78%). However, only a minority of 11% reported using VR regularly. All participants were randomly split into three study conditions. We did not find any significant discrepancies between these groups regarding age, gender, prior VR experience, or immersive tendencies (all $p > .05$). As we searched for differences between the three independent groups, we performed one-way analyses of variances (ANOVA) for all measures. Therefore, we ensured normal distribution with Kolmogorov-Smirnov and homogeneity of variances using Levene's tests. In cases where the data did not meet the latter requirement, we used Welch's ANOVA instead. Depending on Levene's test results, we chose either Tukey's or Games-Howell tests for posthoc comparisons. For legibility reasons, we only report significant differences between the conditions, including all necessary information to ensure reproducibility [64].

6.1 Questionnaires

We assumed that the walking-based implementations lead to higher enjoyment and tension levels. Table 2 depicts the resulting scores of the interest/enjoyment and pressure/tension subscales of the IMI. Only the difference in experienced tension is significant, according to the ANOVA ($p = .005$). Posthoc comparisons indicate that the Gamepad condition elicited significantly less tension than the Tracker condition ($p = .005$; 95% $CI[-1.382, -0.218]$) and the HMD condition ($p = .048$; 95% $CI[-1.169, -0.005]$).

Moreover, we compared the perceived presence between the three study conditions using the PQ questionnaire. As shown in Table 2, only the measure for experienced realism and the total presence score indicate a significant difference. For perceived realism, the posthoc tests show that the conditions Gamepad and Tracker ($p = .003$; 95% $CI[-1.626, -0.298]$), as well as Gamepad and HMD ($p = .002$; 95% $CI[-1.673, -0.346]$) differed significantly. Regarding the total presence, only the difference between Gamepad and HMD ($p = .050$; 95% $CI[-1.037, -0.001]$) is significant.

Further, we wanted to assure that potential cybersickness induced by locomotion would not impede our study. The results of the SSQ are listed in Table 2. The values for the Gamepad condition are significantly higher than for the HMD condition (nausea: $p = .018$; 95% $CI[4.882, 59.990]$, disorientation: $p = .023$; 95% $CI[4.999, 69.241]$). We presume that this difference is related to the used locomotion technique rather than the sneaking mechanism. Most importantly, the values across all groups are low compared to Kennedy et al.'s reference values [27], thus not indicating significant problems with cybersickness in any of the three conditions.

To test our hypotheses, we also assessed individual subscales of the NASA-TLX and PXI. The resulting means and standard deviations are listed in Table 2. The perceived challenge, according to the PXI, differed significantly across the conditions. The posthoc tests indicate that the Tracker ($p = .001$; 95% $CI[0.504, 2.252]$) and HMD ($p = .004$; 95% $CI[0.371, 2.118]$) conditions provided a greater challenge than the Gamepad controls. For the NASA-TLX, only the physical demand subscale reveals a notable difference: the Tracker condition required a substantially higher physical effort than the two other groups (Gamepad: $p < .001$; 95% $CI[24.961, 55.039]$, HMD: $p = .002$; 95% $CI[10.525, 47.475]$).

6.2 Custom Questions and Logging Data

To better understand the participants' expectations and experiences, we also assessed several custom questions. These questions covered three aspects: realism, usability, and liking. Table 3 lists the means, standard deviations, and ANOVA results. In particular, the performed one-way ANOVA reveals notable disparities for five of the ten custom questions. For CQ1, posthoc tests indicate that the Tracker mechanism felt more realistic than the Gamepad approach

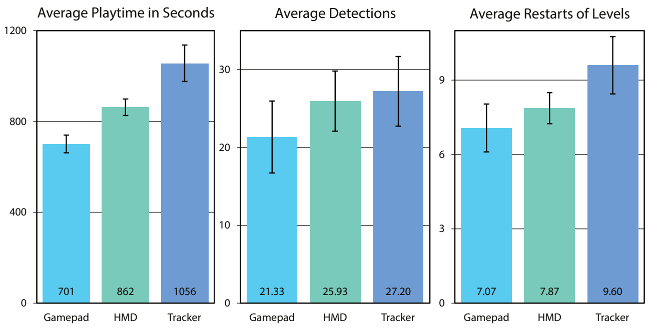

Figure 4: Results from the data logged during the play sessions (means and standard errors). From left to right: The difference in playtime for all study groups in seconds; The average number of audible detections by the NPC guard; The average number of level restarts caused by the players being caught.

($p = .006$; 95% $CI[0.392, 2.674]$). Even though the ANOVA suggests a significant difference for CQ3, posthoc testing could not confirm this assumption.

Concerning CQ4, the Gamepad condition required a substantially lower effort to sneak than the other two groups (Tracker: $p < .001$; 95% $CI[-4.324, -2.077]$, HMD: $p = .001$; 95% $CI[-3.278, -0.855]$). Further, the posthoc test reveals a notable difference between the Gamepad condition and the Tracker ($p = .003$; 95% $CI[-2.962, -0.638]$) and HMD ($p = .010$; 95% $CI[-1.882, -0.251]$) conditions for CQ5. For CQ6, only the difference between Gamepad and Tracker conditions is significant ($p = .019$; 95% $CI[-2.945, -0.255]$).

Finally, we also analyzed the data logged during the play sessions: the total playtime, the number of detections by the guard, and the number of level restarts (see Figure 4). Among those, only the playtime differs significantly across the groups. Compared to the Gamepad condition, subjects in the HMD group played 23% longer ($F(2, 26.33) = 9.410$; $p = .014$; $\eta^2 = 0.327$; 95% $CI[29.808, 293.276]$), and participants using the Tracker approach played even 50% longer ($F(2, 26.33) = 9.410$; $p = .002$; $\eta^2 = 0.327$; 95% $CI[129.543, 580.650]$). However, this discrepancy was not caused by substantial differences in detections or level restarts.

7 Discussion

Regardless of the used sneaking technique, the majority of players enjoyed participating in our study. Subjects explicitly mentioned the potential of sneaking-based interactions for immersive experiences. According to their feedback, this type of gameplay conforms to the key advantage of VR by allowing to *"become someone completely different — like a master spy"(**P29**)*. Most subjects wanted to play more levels (CQ8) and were interested in other sneaking-based VR games (CQ9). But how do the different implementations compare? Where are the individual strengths and weaknesses? Our four hypotheses and two research questions cover the various aspects of player experience and usability necessary to answer these questions.

H1: In comparison to the Gamepad condition, the Tracker and HMD approaches significantly increase the perceived presence.
The results from the PQ indicate that the subjects experienced high levels of presence across all three conditions. However, the two movement-based techniques both scored higher regarding experienced realism. This finding supports our primary research goal of creating a natural and realistic sneaking experience for IVEs. Interestingly, the HMD condition got even minimal higher values for realism and total presence than the precise tracker-based approach. Players in the HMD group even reported having the feeling that *"the guard would hear every loud step immediately"(**P5**)*. It seems that most participants did not notice the inferior tracking fidelity.

H2: The full-body conditions require a significantly higher physical effort compared to the Gamepad controls.
One potential difficulty introduced by our proposed mechanisms is the additional physical demand. The requirement of cautiously placing every foot increases the necessary physical effort for the Tracker condition significantly. While the values for the HMD condition were also higher than for the Gamepad group, this difference was not significant. Also, VR experiences do not necessarily suffer from demanding full-body interactions. In contrast, several participants appreciated the novel challenge as it forced them *"to be fully aware of the own body"(**P34**)*. Especially the tracker-based approach caused the subjects to feel very active (CQ6) and was sometimes as demanding as an *"exergame"(**P1**)*.

H3: The Tracker and HMD conditions significantly increase task difficulty but not the success rate.
The result from the assessed PXI subscale indicates that our two proposed approaches increased the game's challenge significantly. Since both mechanisms are movement-based, players had to stay cautious and canny even in stressful situations. This conflict was especially noticeable when players got detected and had to outsmart the guard to avoid failing the level. Several participants reacted hectically, which sabotaged their goal and usually forced them to restart the level. As a consequence, the players progressed more slowly and carefully. While the subjects' cautious behavior increased the overall playtime, it had no notable effects on the success rate or enjoyment. Since developers typically seek this kind of behavior in stealth games, we consider our approaches' increased challenge to benefit the intended genre.

H4: Movement-based sneaking significantly boosts players' enjoyment and tension compared to the Gamepad approach.
The study's results confirmed our fourth hypothesis only partially. Regarding the participants' enjoyment, we did not find any notable difference between the three groups. Nevertheless, the high scores of the IMI subscale indicate an overall pleasant experience. Especially in the groups using real walking, players sometimes described the gameplay as *"if you were a secret agent in a blockbuster movie"(**P9**)*. Additionally, the tension subscale revealed that our two proposed techniques elicited a significantly higher tension than the gamepad controls. While there is no considerable difference between the more accurate tracker-based mechanism and the more abstracted HMD approach, the results still underline the general advantage of body-based sneaking. These outcomes are also reflected in the oral feedback: *"it is extremely thrilling to play hide-and-seek with the guard after already being detected"(**P22**)*.

RQ1: How do players assess their particular sneaking technique regarding usability, learnability, and realism?
In general, most participants learned to use the particular sneaking technique very quickly. The concepts behind each mechanism were understood intuitively (CQ3) and did not require additional assistance from the study coordinators. Especially the visual noise indicator, attached to the players' hand, was mentioned as a major aid as it helped to *"gain a feeling for the own loudness"(**P14**)*. After the first levels, the participants mostly *"learned the acceptable threshold by heart"(**P10**)* and reduced their use of the display.

Since all three sneaking techniques work differently, the players' difficulties and problems varied as well. Some of the subjects using the gamepad approach reported being challenged by pressing multiple buttons simultaneously, e.g., taking the tablet while sneaking. In particular, participants with no prior VR experience tended to utter this concern. In the other groups, players had to pay more attention to their movement. Later levels increased this challenge by adding obstacles requiring precise timing or crouching. As this hurdle is primarily relevant for the tracker-based approach, subjects in this group had significantly more problems (CQ5). However, it is worth noting that only very few players reported being overstrained (CQ5) or preferring a different technique (CQ7).

Apart from usability and learnability, we were also interested in the realism of our proposed techniques. How do they compare to real sneaking? In general, players tend to adapt to simplifications and abstractions in gameplay elements and usually ignore implausibilities for the sake of a coherent game experience. Therefore, it does not surprise that the participants mostly rejected CQ2. However, asking them personally, subjects articulated more diversified feedback. Especially the binary sneak mode of the Gamepad condition *"did not feel like sneaking but cheating. I stopped using it and controlled my speed manually"(**P3**)*. For the tracker-based sneaking, players liked that *"every step is relevant. I could even stomp to attract attention on purpose"(**P28**)*. This feedback is reflected in the significant difference regarding the realism of the sneaking technique (CQ1).

RQ2: Are there notable differences between the two proposed walking-based approaches HMD and Tracker?

Our proposed implementations fit their intended purpose and provide valuable benefits. Compared to established controls, these approaches can increase the perceived presence, tension, and challenge without causing frustration or exhaustion. However, generally speaking, both proposed techniques performed very similarly, despite the differences in tracking precision. While the accurate tracker-based approach offers some advantages over the HMD abstraction, e.g., more realism and physical activity, these did not significantly impact the player experience. In contrast, the feedback for the Tracker condition was more ambiguous than the overall positive HMD feedback.

The oral feedback points towards the most likely reason: with the hardware trackers, players must pay attention to every single step they take. In contrast, the HMD approach focuses on the players' intentions. Precisely speaking, the mechanism is based on the assumption that sneaking players walk slowly. Despite being unaware of the actual implementations, players intuitively understood this concept. The HMD approach delivers a comparable experience to precise tracking while requiring less attention and being more forgiving. Therefore, it might fit the players' expectations better.

Furthermore, the HMD implementation relies only on standard hardware and does not require any additional tracking devices. Considering both properties, we conclude that the HMD-based approach is most suited for consumer-oriented experiences, i.e., VR stealth games. In contrast, the hardware trackers can guarantee far more precise footstep tracking necessary for enhanced realism and additional gait-based interactions that are not possible with the HMD abstraction, e.g., stomping. The technique also builds upon Vive's marker-based tracking and is therefore easily applicable to every VR scenario. These benefits make our approach valuable for other use-cases as well. For instance, accurate footstep tracking is useful for a variety of physical activities such as dancing or in specific simulation or training applications.

8 Limitations

In our study, we compared our two movement-based approaches against the commonly used gamepad controls. This decision was motivated by the observation that current stealth VR-games tend to rely on button-controlled sneak modes and joystick locomotion. Nevertheless, the chosen study setup raises the question of whether our findings may instead originate from this difference in locomotion techniques. While we indeed attribute a notable influence to the particular navigation method, the overall low levels of cybersickness paired with the similar enjoyment levels indicate a comparable user experience across the groups.

Further, we focussed entirely on the fundamental sneaking mechanism, comprising a simple binary differentiation between walking and sneaking. Consequently, more complex interaction patterns, such as the introduced stomping concept, were not included in the study scenario. Especially stomping is an interesting concept, as it introduces an additional degree of input fidelity, namely exceeding the sneaking-threshold deliberately. However, such interactions are not easily realizable for the Gamepad and HMD approaches without adding additional buttons. Since this step would have introduced an additional variable for our study, we decided to test the basic sneaking concept in isolation.

Finally, we decided against any avatar visualization except for the players' hands. This decision was mainly motivated by the differences in tracked devices: Only one condition featured positional feet tracking. Therefore, displaying virtual feet would have introduced an additional variable to our study. Instead, we point to the existing work on virtual avatars as the underlying effects were already extensively covered. Similarly, we decided to base our detection algorithms solely on the visibility of the HMD. Thereby, we assured comparability and avoided frustration caused by peeking limbs. Nevertheless, using the players' fully tracked and visualized bodies for the detection mechanism might significantly influence the players' behavior and the measured effects.

9 Conclusion and Future Work

Virtual reality games provide the unique opportunity to slip into the role of the own favorite character and experience a thrilling adventure first-handed. One of these stories may involve a top-secret agent on his almost impossible mission to save the world. Therefore, the agent must infiltrate a restricted area and secure confidential files. While players can already encounter similar plots in available VR games, these often lack to convey a satisfying stealth experience. In most cases, players only need to stay out of sight of the probably deaf guards. Stepsounds rarely have any influence on the gameplay. This simplification does not use the full interaction fidelity of sneaking activities and limits the achievable scope of realism.

With our work, we have explored the potential of sneaking as a novel input modality for such IVEs. Therefore, we developed two gait-oriented mechanisms to capture the users' gait. The first measured the feet's deceleration, while the second used the average HMD speed as a proxy. We then compared the two approaches against the established gamepad controls. Our study's results revealed three interesting takeaways:

1. The experiments confirmed that players generally appreciated sneaking-based gameplay elements.

2. Our proposed implementations increased the perceived presence, tension, challenge, and physical activities without overcharging or exhausting the players.

3. Both approaches performed very similarly, despite the differences in tracking fidelity and degree of abstraction. In most cases, it is not necessary to capture exact foot movements, as the HMD-based implementation provides a similar experience.

In our future research, we will concentrate on further use-cases of the proposed interaction concepts. In particular, our tracker-based mechanism opens interesting research directions. It enables precise detection of the users' steps, which could be used for other movement-intense activities, such as dancing. While we mainly focused on differentiating walking and sneaking, our tracking mechanism was also capable of detecting stomping and jumping movements. In the future, we want to extend this concept to identify more types of gait. Especially training simulations could profit from this capability to provide individual gait-understanding feedback. Finally, we aim to combine the proposed gait-based sneaking with additional channels, namely synchronized audio feedback, voice detection, haptic feedback, and full-body tracking, to achieve a fully lifelike sneaking experience.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	**"I Packed My Bag and in It I Put...": A Taxonomy of Inventory Systems for Virtual Reality Games** *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Toward a Taxonomy of Inventory Systems for Virtual Reality Games

Sebastian Cmentowski, Andrey Krekhov, Ann-Marie Müller, and Jens Krüger. 2019. Toward a Taxonomy of Inventory Systems for Virtual Reality Games. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts (CHI PLAY '19 Extended Abstracts)*. ACM, Barcelona, Spain, 363–370. DOI: 10.1145/3341215.3356285.

"I Packed My Bag and in It I Put. . . ": A Taxonomy of Inventory Systems for Virtual Reality Games

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Abstract
Virtual reality (VR) games are gradually becoming more elaborated and feature-rich, but fail to reach the complexity of traditional digital games. One common feature that is used to extend and organize complex gameplay is the in-game inventory, which allows players to obtain and carry new tools and items throughout their journey. However, VR imposes additional requirements and challenges that impede the implementation of this important feature and hinder games to unleash their full potential. Our current work focuses on the design space of inventories in VR games. We introduce this sparsely researched topic by constructing a first taxonomy of the underlying design considerations and building blocks. Furthermore, we present three different inventories that were designed using our taxonomy and evaluate them in an early qualitative study. The results underline the importance of our research and reveal promising insights that show the huge potential for VR games.

Author Keywords
Virtual Reality Games; Inventory; Taxonomy; Interaction; User Interfaces; Virtual Environments; Usability

CCS Concepts
•**Human-centered computing** → **Virtual reality;** *Graphical user interfaces;* •**Software and its engineering** → **Interactive games;** Virtual worlds software;

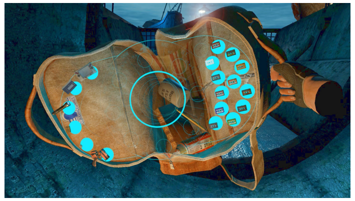


Figure 1: Virtual backpack used as inventory in the game *The Gallery - Episode 1: Call of the Starseed* [3].

Figure 2: The linear quick bar for frequently used items in the game *Minecraft* [12].

Figure 3: The inventory of the game *Green Hell* [5] is structured by the player alone.

Motivation

More and more players immerse themselves in virtual environments. Head-mounted displays (HMDs) and tracked hand controllers enable unmatched levels of agency and interactivity and can provide an enjoying experience in virtual reality (VR). In an effort to enrich the player experience even further, latest research work has already tackled a broad set of challenges: Novel navigation techniques [4, 9] allow the players to explore vast open worlds on their own and intuitive controller designs [10, 18] transform these worlds into interesting and interactive experiences.

However, many VR games still fail to reach the complexity of traditional digital games. One example of typically overlooked features is the in-game inventory [17]. It allows players to acquire new tools and goods throughout their journey and plays an important role in character development. In this work, we establish a starting point for this important topic. Our main contribution is the construction of a first taxonomy covering the broad design space of inventories in VR games, including the different requirements and design possibilities. Based on this preliminary taxonomy, we present three different inventory systems: *Flat Grid*, *Virtual Drawers*, and *Magnetic Surface*. The prototypes were evaluated in a small-scale qualitative study to gather first insights. The player feedback is used to generate early design implications and potential future research questions.

Design Considerations for Inventories

The use of inventories dates back to the beginning of digital games as such [6, 13]. They have yet evolved into a standard feature that is used in a majority of current games. Even though the use of VR introduces additional challenges and novel design possibilities, the major purpose of these interfaces stays the same: storing items. The success of a particular implementation depends on various design decisions that impact four crucial factors: *comprehensibility*, *interactivity*, *contextual embedding*, and *personalization*.

Comprehensibility. The information for every item that is currently stored in an inventory needs to be displayed in a comprehensible manner. Displaying too many items or meta-information at once on a limited screen can easily lead to visual cluttering. This increases the necessary mental effort and processing time exponentially and can easily spoil the whole gameplay [15].

Interactivity. In general, managing and interacting with the inventory and the stored items should be as easy and quick as possible. In extreme cases, situation-dependent controls could be used to simplify the necessary user actions to a minimum. However, such game designs bear the risk of reducing the feeling of agency [15]. Especially, in VR games, players like to interact with the environment and to feel in control over the resulting actions.

Contextual Embedding. Ultimately, each inventory needs to fit the game's context and purpose. Most implementations can be subdivided into two general groups: The *carry* mode focuses on few, quickly accessible items, whereas the *loot* mode requires easily manageable storage [8, 15]. A typical example of a pure *carry* mode is the game *Fortnite* [7], whereas the inventory system of *Diablo III* [2] is a perfect remedy for *loot*-based games.

Personalization. The role of inventories as personal and individual space has a huge impact on the game experience. Especially in linear games, players usually have little to no chance to individualize their gameplay. The only true exception is an inventory, where they have complete freedom over content and organization [15]. Therefore, freely manageable inventories can provide significant advantages to character identification and presence.

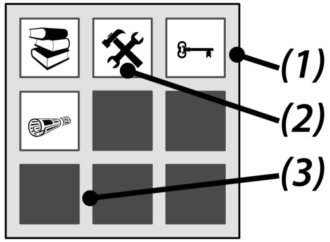
Taxonomy of Inventories

(1) Inventory Interface:
- *type:* overlays, virtual objects, real proxies
- *position:* static or moveable
- *style:* thematic or realistic

(2) Item Representation:
- *design:* realistic or abstract
- *scale:* scale-preserving, miniaturizing, normalizing

(3) Item Arrangement:
- *layout:* linear, grid, ring, slots, unrestricted
- *capacity:* unlimited, fixed, dynamic
- *ordering:* unstructured, sortable, sorted
- *improvements:* categories, hierarchies, stackability

(4) Interaction:
- *open/close:* click or gesture
- *adding items:* automatic or manual
- *item manipulation:* raycast-based or physical action



Building Blocks of Inventories for VR

Inventories are more than simple user interfaces and consist of multiple different components that need to be taken into consideration. In this section, we decompose the inventory into atomic building blocks for a better understanding and analysis.

Inventory Interface

The interface is the basic building block that contains all storage items and determines the position, shape, and design of the whole inventory. In contrast to traditional digital games, the use of VR introduces a whole range of possible interface types. Apart from simple overlays such as the 2D user interface in *SteamVR Home* [16], the inventory could be presented as a virtual object in the world. This includes moveable items such as the backpack inventory in *The Gallery* [3] (cf. Figure 1) and fixed access points, e.g, chests or mailboxes. Alternatively, it is possible to attach the inventory directly to the player. A typical example is the virtual belt in the game *Batman: Arkham VR* [14]. Another intriguing approach to further increase realism and agency is the use of a collection of real physical proxies [10, 18].

Inventories in VR games must be placed in a 3D virtual environment which introduces the depth as an additional parameter. Depending on the positioning in relation to the player, the inventory might be occluded by the surrounding or could obstruct the player's view. Both cases usually lead to frustration and decreased usability. Therefore, it might be favorable to give the player the chance to move the storage freely or hide it completely. This feature could also provide further benefits in terms of personalization and interactivity.

Usually, VR applications would try to maximize the player's immersion into the virtual scenery and to avoid any thematic cuts. Therefore, it seems natural to match the inventory's style as closely as possible to the surrounding environment. On the other hand, abstract menus offer the advantage of prior knowledge: Most people have already experienced a storage interface of any kind and should be proficient to a certain degree. Therefore, a more abstract design could help to reduce the necessary cognitive load.

Item Representation

Every in-game item placed within the inventory needs a graphical or textual representation. The chosen concept strongly influences the type and amount of information that is conveyed to the player. Realistic designs allow for detailed conclusions on the object's shape and physical properties, while also merging into the virtual scenario. In return, a more abstract style, e.g., icons or texts, reduce the visual clutter and make it possible to increase the information density for each item. It is to note that the choice between a 2D and 3D representation is not directly linked to the degree of realism. Instead, this decision is usually based on the type of inventory interface being used.

One key aspect of the chosen representation is the displayed size: Preserving the original physical scale of objects does not only allow players to draw conclusions on relative ratios and actual sizes but makes it possible to remove any discrepancy between the real item and its representation in the inventory. However, this design choice bears the risk to quickly fill the limited inventory space with large items and introduce new problems such as item occlusion. The alternative is to miniaturize or normalize the item's scale when adding the object to the inventory.

Item Arrangement

The arrangement of the various items in the inventory is at least as important as the representation itself. Depending on the actual use case, the layout should be focused on either accessibility, management, or overview of the content. In digital games, the most common choices are

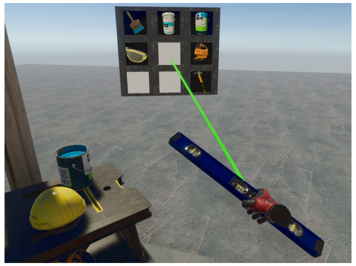


Figure 4: Items are added to the *Flat Grid* using raycast aiming.

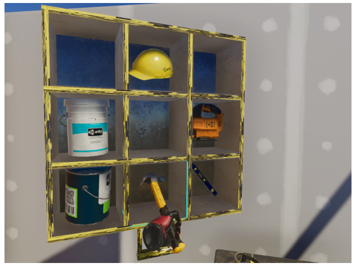


Figure 5: The *Virtual Drawers* contain equally-scaled items.

Figure 6: Players can move the inventory using a handle.

linear shapes for *carry*-inventories, such as the quick bar in *Minecraft* [12] (cf. Figure 2), and grids, e.g., in *World of Warcraft* [1], when dealing with larger amounts of items. Other possible designs include ring menus or fixed slots. For immersive experiences aiming to increase presence and personalization, it seems likely to provide more freedom to the player. However, free object placement bares the risk to produce obstructive and chaotic inventories that miss the forced ordering through grids. Nevertheless, this drawback could be used as a gameplay mechanic, like in the survival game *Green Hell* [5] (cf. Figure 3).

A common problem of many games is a cluttered inventory providing poor comprehensibility and overview. Reasons are either massive storage sizes or extreme information densities. The easiest solution is a limitation of the inventory capacity or a reduction of the provided information per item. Many games decide to include an additional feature to extend the maximum storage during the journey. However, this step should be combined with an increase of the interface size to preserve the relative information density.

In addition to the particular item arrangement strategy, inventories provide different amounts of automatic ordering. This ranges from complete flexibility and self-administered organization, through optional sorting techniques, to fixed arrangements such as the LIFO (last in, first out) approach. After all, inventories in VR should maximize the player's freedom and control over the item arrangement without sacrificing too much comprehensibility. The overview could be improved by including optional concepts such as different categories, hierarchies, or stackability of items. Nonetheless, only the minority of these features have been used in VR games yet and it remains to be investigated whether these can be combined with other aspects such as realistic item representation or free object arrangement.

Interaction with Inventory

VR offers completely new interaction approaches using tracked controllers and spatial movements. Therefore, the underlying interactions with the inventory are by far the most intriguing difference in comparison to non-VR games. Instead of using a simple button click, games could implement more natural and interactive ways to open the inventory. A perfect example is *The Gallery* [3], where players reach behind themselves to retrieve a virtual backpack. Additionally, it is easy to give the players full control over the position and orientation of the inventory and allow them to drag it around freely. This opens novel design concepts and provides a very high level of interactivity.

The by far most important mechanism is adding and removing items in the inventory. Many non-VR games tend to collect items automatically. However, this approach is less favorable for VR-games. Instead, they could greatly profit from a manual pick-up-process to improve the player's agency. This could be achieved either through more abstract raycast-aiming or more natural and physical gestures. Especially direct interactions with virtual objects outperform distant object selection and manipulation significantly [11].

Inventory Designs

The main goal for designing different inventories was to cover the most interesting aspects of the taxonomy and gather first valuable insights. The chosen number of three implementations avoids binary opinions and instead encourages players to provide detailed and in-depth feedback. At the same time, the limited amount prevents subjects from getting lost and potentially frustrated. Our designs differ in various aspects, such as the interface type, item style, or underlying interaction concept. To avoid arbitrary feedback and ensure comparable results, we defined a set of three rules that are shared between all prototypes:

Figure 7: The *Magnetic Surface* allows for fine-graded positioning.

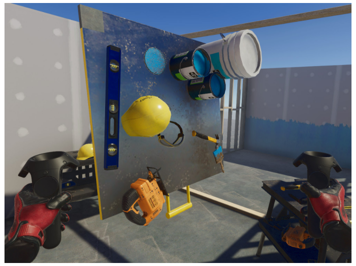


Figure 8: Items stick to the *Magnetic Surface* until removed.

Figure 9: The construction scenario used as testbed game.

1. A realistic and consistent style is preserved.
2. The inventory is activated with a single button click and starts at a fixed position in the virtual world depending on the player's view.
3. There are no additional features such as sorting, categories, hierarchies, or item stackability.

Flat Grid
The first inventory design is a flat two-dimensional overlay that is placed at a static position $1.5m$ in front of the player's head upon activation. The stored items are arranged using a regular grid of three times three virtual slots. This fixed size is chosen to provide some degree of variety for object placement while also mimicking the case of a limited inventory. Each object in the inventory is presented as a realistic 2D image. This prototype closely matches the most common menus in current VR games (cf. *SteamVR Home* [16]). It should provide a simple and comprehensible design that lacks realism and free object placement.

The interaction with the inventory uses raycast pointing: Players could point at an occupied slot and press the button for grabbing objects to retrieve the item. Similarly, releasing an object while pointing at an empty slot would insert the item into the inventory (cf. Figure 4). This interaction design is consistent with the other prototypes in terms of the necessary buttons and expected behavior but replaces natural grabbing through an abstract raycast aiming.

Virtual Drawers
The second design shares the same grid of nine slots as the *Flat Grid* inventory. However, it is displayed as a virtual 3D shelf floating in the world (cf. Figure 5). The stored items are placed on one of the shelf boards as realistic 3D shapes that are scaled to a normalized size to fit the available space. The items are added to the inventory by placing them physically into one of the slots instead of using raycasts. Players have the opportunity to grab the whole inventory using a handle located at one side and move it freely within the environment (cf. Figure 6). In contrast to the *Flat Grid*, this design features a more realistic appearance and includes more natural and direct interaction.

Magnetic Surface
The last inventory is a simple metallic work-plate floating at a convenient position to the player's side (cf. Figure 7). Similarly to the *Virtual Drawers*, the plate can be positioned freely in the world using an attached handle. This inventory provides the most freedom and control to the user: it avoids any forced organization in the form of grids but uses a magnetic force to stick all stored items to the surface of the work-plate (cf. Figure 8). Players can simply put any object onto the plate using natural interaction and it will preserve the chosen position and rotation, as well as the item's original scale and shape. Consequently, this inventory has no maximum capacity or fixed density. Instead, the players are in full control over item arrangement and positioning. They can even use the physical properties of held items to push other stored items around.

Evaluation and Discussion

We executed an early qualitative study with 8 participants (3 female, mean age: 29.1, $SD = 6.19$) to gather insights into how players would use and experience the different inventories. The used scenario was a virtual construction ground featuring all kinds of tools and materials (cf. Figure 9). This provided a suitable testbed for the evaluation as it allowed the participants to interact with various different items and simulate different uses of inventories (cf. Figure 10). During the study, the subjects were briefly introduced to all three prototypes in random order. They were encouraged to explore the different features on their own and provide feed-

Figure 10: Players used various items to test the inventories.

*"The abstract nature of the flat grid somehow contradicts my expectations towards an immersive VR-game." (**P1**)*

*"I would love to empty the virtual drawers by turning them upside down." (**P2**)*

*"I miss the stackability of similar items." (**P5**)*

*"The magnetic surface is like a scratchpad where I can arrange everything to my needs." (**P8**)*

back in an audio-recorded think-aloud process. After examining all aspects of the current inventory to a full degree, the subjects could move on to the next implementation while having the option to return at a later time.

In general, the feedback for all inventories was very positive. Every participant was able to learn the underlying concepts quickly and provide detailed feedback. One major concern with all designs was the occlusion problem between environment and inventory. As VR inventories have to be placed within a 3D scenario, they can easily obstruct important content or appear behind other objects. This weakness was partially fixed by the option to grab and move the inventory to custom spots. This technique allowed for more personalization and was the most appreciated feature throughout the study. An interesting request from one participant was to reduce the setup time by *"restoring the previously adjusted position relative to the head"(**P3**)*.

Being asked for their personal favorites, almost all participants gave a similar ranking beginning with the *Flat Grid* as the least interesting choice and the *Magnetic Surface* as the clear winner. At first sight, this contradicts the feedback for the *Magnetic Surface* being described as the least scaleable, structured, and productive of all three inventories. However, players clearly emphasized the importance of interactivity, authenticity, and realism. One of the explicitly-named influencing factors was the shape- and size-preserving behavior of the *Magnetic Surface* prototype. A common suggestion was to implement this feature into the *Virtual Drawers* by *"resizing the shelf boards automatically to fit any item at its original scale"(**P5**)*.

Even though most VR applications use raycasts to interact with menus, most participants initially tried to use the *Flat Grid* by placing items with physical grabbing. This is a clear sign towards the superiority of natural interactions.

Finally, we asked the subjects to propose use-cases for every inventory. The broad consensus was to choose the *Flat Grid* for efficiency in larger and more loot-based games. One participant mentioned an interesting approach to increase the performance even further: *"inserting an item to an occupied slot should swap both items to avoid additional steps"(**P1**)*. The virtual drawers were generally preferred as a more interactive alternative that is best suited for larger worlds and manageable item counts. Both approaches were described as *"storage inventories"(**P7**)* for less often used items. Finally, the *Magnetic Surface* was sometimes called *"working storage"(**P8**)* and was preferred for few regularly used carry-items. Interestingly, some participants liked the idea of using this inventory in multiplayer games to provide mutual storage shared by all players.

Conclusion and Future Work

We proposed a first step toward the use of inventories in virtual environments. Our preliminary taxonomy explains the necessary considerations, building blocks, and potential design choices to be considered when creating inventories for VR games. Our qualitative study supports our basic assumption that these interfaces could provide novel game mechanics and improve game experience and enjoyment. The detailed player feedback revealed first interesting insights backing our taxonomy approach and hinting toward additional parameters and design considerations such as the occlusion problem. In our future work, we will refine and extend the existing taxonomy to incorporate additional player and developer input. Additionally, we suggest investigating the overall significance of storage systems in VR games to explore the effects of these interfaces on the game experience. The ultimate goal is to build a fundamental research body on VR inventories incorporating a comprehensive taxonomy and a set of design guidelines to be used by researchers and practitioners.

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"I Packed My Bag and in It I Put...": A Taxonomy of Inventory Systems for Virtual Reality Games

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***Abstract*—On a journey, a backpack is a perfect place to store and organize the necessary provisions and tools. Similarly, carrying and managing items is a central part of most digital games, providing significant prospects for the player experience. Even though VR games are gradually becoming more mature, most of them still avoid this essential feature. Some of the reasons for this deficit are the additional requirements and challenges that VR imposes on developers to achieve a compelling user experience. We structure the ample design space of VR inventories by analyzing popular VR games and developing a structural taxonomy. We combine our insights with feedback from game developers to identify the essential building blocks and design choices. Finally, we propose meaningful design implications and demonstrate the practical use of our work in action.**

***Index Terms*—virtual reality, inventory, taxonomy, game design**

I. Introduction

Inventories are among the most common features in various game genres. Dating back to the beginning of digital games, inventories have evolved from pure item collections storing the players' possessions to sophisticated gameplay features. The range of use cases includes storing and switching items, displaying information, and managing the inventories' contents. Recent games have discovered the inventory as part of the game world and introduced mechanics to make the storage interface more compelling. The game *Green Hell* [1] demonstrates how inventories can seamlessly blend into the main gameplay by forcing players to rotate and align their items carefully to fit within a very confined space.

One game platform getting notable attention throughout the last few years is virtual reality (VR). Players use head-mounted displays (HMDs) and tracked controllers to replace their real surroundings with a virtual world. However, one crucial prerequisite to guarantee a compelling and immersive experience is a proper interaction concept. Considering that inventories are the cardinal point of object interaction in many games, they could also provide a compelling addition to the VR experience. Allowing players to carry their found items and building personal storage is a natural addition to this interaction-centered gameplay. Unfortunately, most VR developers still refrain from using inventories and thus fail to reach their game's full potential and profundity.

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The causative reasons are plentiful and mostly reside within the additional requirements, such as the inventory's positioning. In contrast to desktop games, VR titles must place the interface in the players' sight without obstructing the surrounding. At the same time, players experience the virtual environment as a substitute for reality, leading to an increased sensitivity for incoherent and unnatural interactions. These obstacles make it challenging to transfer existing non-VR inventories to the virtual world. For instance, an abstract 2D menu works well for desktop games but performs poorly in VR [2].

Applying existing research on VR menus to inventories is also not trivial. Most other user interfaces, such as game settings, are designed as abstract overlays prioritizing interaction speed and simplicity. In comparison, inventories are closely tied to the virtual environment and require completely different interactions. For instance, adding an item to the inventory means transferring it from the 3D world to the local storage interface. This transition might even include a resizing or remapping to 2D. In sum, designing storage systems for VR is by no means a trivial task. Paired with a general lack of focused research, these challenges provide a strong motivation for a closer look at VR inventory design.

Our work aims to bridge this gap by forming a structural research foundation, encompassing the status quo, and highlighting interesting research directions. Our main contribution consists of three parts (cf. Figure 1). In the first segment, we assess the current state of the art. Therefore, we summarize the relevant related research, collect detailed feedback from active developers and practitioners through semi-structured interviews, and provide an in-depth analysis of current VR games that use inventories as part of their gameplay. In the next part, we combine all three pillars into a condensed framework, which consists of user- and game-related requirements and a comprehensible structural taxonomy summarizing the essential building blocks. As the final step, we demonstrate the practical applicability of our work. We use the presented framework to design three inherently different inventories. This design process is used to discuss the remaining open questions, in particular, the effects and connections between requirements and design choices. This work is meant to build a foundation and inspire future research on this unexplored and multi-faceted topic by raising interesting open questions.

II. Related Work

Despite being one of the most common elements in games, only two closely related works address inventories in VR: Wegner et al. [3] compare two concepts for their suitability in serious games, and Cmentowski et al. [4] present different inventory designs and establish an early taxonomy. Considering the sparse pool of closely related work, we briefly introduce the most relevant work dealing with VR menus in general. For a detailed overview of menus and interactions in virtual environments, we point to the work by Dachselt et al. [5], Kim et al. [6], and Bowman et al. [7]. Unfortunately, the established insights are only partially applicable since inventories differ from most of the researched interfaces. Unlike other menus, such as game settings, inventories should blend into the active gameplay and support a specific set of interactions.

In one of the earliest works on virtual menus, Jacoby et al. [8] present seven interaction aspects: *invocation, location, reference frame, cursor, highlighting, selection, and removal*. These terms partially overlap with the design characteristics *placement, selection, representation, and structure* given by Bowman et al. [7]. We have arranged these terms into three basic categories:

- Layout: *representation, structure*
- Placement: *location, reference frame*
- Interaction: *invocation, removal, highlighting, selection*

A. Layout

Menus in virtual environments come in various shapes and appearances, depending on the use case. Often, menus closely match the scenario's visual appearance, which ensures a consistent experience and benefits the overall game experience [9]. Other designs preserve a neutral and abstract style, making them familiar and easily recognizable as archetypes of their kind [3], [5]. Apart from designing the menu itself, research has focused on the menu items' layout and geometry. Over time, many prominent approaches have been proposed, such as the *TULIP* menu [10] or the *Command and Control Cube* [11]. Many publications have covered the differences between various layouts regarding efficiency and intuitiveness [12]. As these approaches mainly have emphasized the fast selection of few distinct menu options, the results are not applicable to inventories aiming to easily manage dozens of items.

B. Placement

A major challenge when developing VR menus is the third dimension. In contrast to desktop applications, the menu can be positioned freely within the virtual environment. The additional degree of freedom can easily lead to occlusion effects between the world and the interface [8], [13], which are prevented by allowing the players to rearrange the menu at need [13]. Before placing the menu into the virtual world, developers must decide on the point of reference. Dachselt et al. [5] present five possible domains: *world, object, head, body, device*. Past research has emphasized the benefits of bodily interactions: Exploiting the human proprioception could compensate partially for the missing haptic feedback [14]. Nevertheless, attaching menus to the player's body bears the risk of exhaustion through constant muscle activity [13].

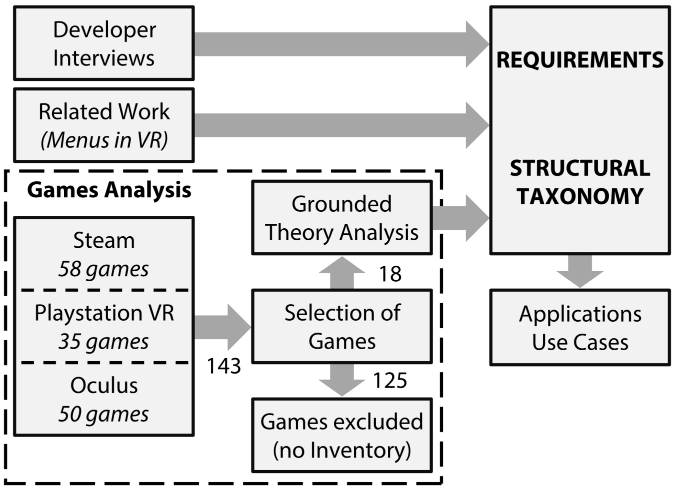

Fig. 1. Flowchart illustrating our research process, including the related work, developer interviews, and games analysis.

Further, menus can be categorized as either *diegetic* or *non-diegetic* [15]. A *diegetic* menu is placed within the scenario and can be used just like any other interactable. This feature offers substantial benefits to presence and player experience, but it usually requires visual embedding and a more realistic reference point, such as the player's body.

C. Interaction

Interacting with menus comprises three actions: opening, closing, and moving. The first two controls are usually implemented using buttons or simple gestures [15], [16] whereas moving menus requires at least a three-dimensional (3D) input. Apart from these features, most research has focused on the interaction with the menu items. Choosing items is decomposed into two sequential subtasks: *highlighting* and *selecting* [6], [8]. Players position a pointer in 3D space to highlight an item and confirm their selection with a button click. For a comparison of different highlighting and selection techniques, we point interested readers to the work by Argelaguet and Andujar [13].

Many standard VR menus have been taken from desktop applications and modified for use in virtual environments. However, using 1D or 2D interfaces in a 3D surrounding increases the complexity and may induce interaction errors [2]. Also, menus can be quickly out of reach for physical actions [8]. Therefore, a popular selection technique is the virtual raycast [12], [16], which requires only minimal muscle activation [13] and can target menus at every distance. An alternative is the virtual hand, with which players use spatially tracked controllers to interact with objects like in the real world. Although slower, more tedious, and limited to the user's range, this approach provides benefits to agency and presence [17]. Many applications use raycasts for menus and virtual hands for all other gameplay interactions. Poupyrev et al. [18] did not find differences between the techniques regarding error-rate or selection speed.

III. Gathering Input from Developers

A major step towards a comprehensive guideline that can help practitioners in their design process is to ask the community. This decision ensures the practicability of the results and prevents working in an ivory tower. Therefore, we recruited twelve experienced VR game developers from different studios through various VR developer channels, such as Discord, and questioned them using a semi-structured interview. A team member with no experience in the communities held the conversations to avoid any bias through prior contacts. Our primary research questions were:

- RQ1: How important are inventory systems for VR games?
- RQ2: How difficult is the design and development process?
- RQ3: Are the available resources a sufficient aid?
- RQ4: What are the unique requirements and challenges when implementing inventories for virtual scenarios?

Even though all participants received the same questions, the interviews mostly followed personal experiences. We analyzed the interview data using a peer-reviewed deductive thematic analysis [19]. The four predetermined main themes followed our initial research questions: Importance/Benefits, Perceived Difficulty, Helpful Resources, and Unique Challenges.

RQ1: *How important are inventory systems for VR games?*

All participants agreed on the general importance of such interfaces for VR games, as they could provide essential benefits to the game and development process. The most frequently mentioned advantage was a more straightforward design phase when adding multiple abilities to a game. Instead of requiring complicated controls, developers could rely on *"a bunch of distinct tools and a common space to store them"(**D2**)*. This approach is especially valuable, considering the limited amount of available buttons on each controller. Another benefit lies within the nature of an inventory: Storing and carrying multiple items enables *"novel gameplay techniques and a deeper storyline"(**D5**)*. Interestingly, one participant reported limiting storage to handheld items. Players are forced to decide carefully what to carry with them and to remember where they left things. This approach is the minimalist version of a fixed capacity inventory not requiring any additional interface.

RQ2: *How difficult is the design and development process?*

The second question split the participants into two groups. Half of the developers stated they were actively avoiding the use of inventory systems at all, despite its vast potential. The main reason is the high complexity of the design and implementation phase. Considering the mainly small team sizes, most developers could not afford to spend extraordinary resources on developing such a challenging feature. Even though the other half used inventories in most games, they reported requiring significant development time and multiple iterations since *"it just did not feel natural"(**D1**)*. Overall, the subjects described the topic as being highly complicated and requiring detailed domain knowledge.

RQ3: *Are the available resources a sufficient aid?*

Ten of twelve subjects noted that inventories are among the most complex VR techniques that receive subpar attention. Being asked what could aid them in their situation, most developers preferred *"having an off-the-shelf asset to handle it"(**D9**)*. However, the requirements for such a component would be immense since every game requires *"creating a style that looks and feels natural"(**D11**)*. Other commonly requested resources are general guidelines or tutorials on developing inventories that convey a good user experience. Both requests require detailed domain knowledge in a novel research area. We want to address these issues by organizing the design range with precise requirements and a clear structure.

RQ4: *What are the unique requirements and challenges when implementing inventories for virtual scenarios?*

One benefit of virtual setups is the ability to become fully immersed in the scenery with high levels of agency and presence. The participating developers emphasized this unique advantage and underlined the importance of preserving a consistent and natural experience. Inventories should be placed within the virtual world and *"must not appear as an artificial overlay"(**D12**)*. Furthermore, the use of two-dimensional (2D) interfaces is strongly discouraged. Most developers described such inventories as detrimental to the player experience: *"If it is just another flat 2D experience in VR, I feel that will shatter the immersion – which is what VR is all about"(**D4**)*.

Another critical challenge is the positioning of the inventory. The 3D nature of virtual scenarios adds additional difficulty to visibility and usability. Many developers aim for free locomotion within the world, without limiting the accessibility of the inventory: *"Menus and controls must be placed far enough away from the player as to not crowd them, yet close enough to interact"(**D7**)*. One commonly used approach is to attach the inventory directly to the player itself. However, VR players are usually not fully tracked and will not see their own body except the hands. This impediment hinders inventory attachments: *"A belt seems awkward, backpacks seem to stop the game, wrist-based seems the best so far"(**D9**)*.

Finally, the developers emphasized using the full range of available controls to convey a realistic and fun experience. Pointing and clicking are well-known interactions that closely resemble traditional computer usage but lack natural counterparts. Instead, subjects prefer fully tracked controllers (6DOF) to implement standard grabbing behavior. Combining this feature with context-sensitive gestures could achieve even more intuitive and realistic controls: *"A reach over the shoulder is a great system for grabbing a weapon"(**D8**)*.

The overall feedback shows that inventories are an exciting and relevant topic. The various concerns, problems, and challenges faced by VR developers underline the need for sophisticated guidelines. The answers to RQ3 demonstrate that the currently available resources, best practices, and current games are not of sufficient help. Therefore, this work provides a first structural approach to this vital topic.

TABLE I
THE LIST OF ALL 18 EXAMINED VR GAMES FEATURING INVENTORIES.

Platform	Genre	Game	
PlayStation	role-playing	The Elder Scrolls V: Skyrim VR	[20]
PlayStation	action	The Mage's Tale	[21]
PlayStation	adventure	ARK Park	[22]
PlayStation	action	No Man's Sky VR	[23]
Steam	role-playing	Crawling Of The Dead	[24]
Steam	role-playing	Vanishing Realms	[25]
Steam	simulation	Afloat	[26]
Steam	shooter	Arizona Sunshine	[27]
Steam	survival	Castaway VR	[28]
Steam	survival	Star Shelter	[29]
Steam	survival	The Forest VR	[30]
Steam	shooter	Half-Life: Alyx	[31]
Oculus	role-playing	Asgard's Wrath	[32]
Oculus	survival	Subnautica	[33]
Oculus	shooter	Onward	[34]
Oculus	shooter	STAND OUT: VR Battle Royale	[35]
Oculus	adventure	Batman: Arkham VR	[36]
Oculus	adventure	The Gallery - Call of the Starseed	[37]

TABLE II
EXEMPLARY GAME OBSERVATIONS FROM THE FIRST ANALYSIS STEP.

Feature	Observation
title	Crawling of the Dead [24]
platform	Steam
layout	shape: backpack (fitting game's theme)
	menu: 2D, floating in front of bag
	structure: mix of purpose slots & grid
	items: miniaturized versions of original object
placement	reference: virtual object floating in the world
	position: players place inventory freely in front of them
interaction	open/close: use gesture
	collect: automatic (touching) & manual (virtual hand)
notes	sorting partially possible (free slots), except loot

IV. Analyzing VR Games Using Grounded Theory

After reassuring ourselves of the demand for a general guideline through developer interviews, we conducted a qualitative study on inventories in VR games to identify the essential building blocks and design choices. We used a grounded theory approach adapted from the analysis of idle games by Alharthi et al. [38]. *Grounded theory* [39]–[41] is used to explore novel domains and build a theory from collected data. The approach consists of three steps: In *open coding*, the collected data is structured by applying preliminary labels. The resulting codes are combined into concepts sharing a common theme. These results are further refined in *axial coding* by identifying relationships between the codes and concepts to merge them into categories. Finally, *selective coding* is used to form a general theory using the established categories. Our analysis process, seen in Figure 1, encompassed four consecutive steps: games-selection, initial observations, open coding, and axial and selective coding.

Step 1: Selecting VR Games

We started by identifying VR games that feature inventories. Despite the late popularity, the overall corpus of VR games remains sparse. Many of the available titles are merely demos of non-VR games or experimental micro-games. Additionally, most of the games are distributed on more than one platform. Therefore, we decided to include only distinct games featuring enough content for evaluation and having at least ten reviews in the stores. From the three biggest platforms, *Steam* [42], *Oculus* [43], and *PlayStation VR* [44], we chose a total of 143 games. We reviewed all games to determine whether a title was appropriate for our analysis and excluded games with no or minimal inventories. For instance, the game *Moss* [45] featured a menu button to switch between three different styles of the hero's main weapon. Considering this option was purely cosmetic; it did not add any value to the gameplay. In the end, we finished with a corpus of 18 VR-games (see Table I).

Step 2: Observations

Two researchers went through all 18 games, using trailers, game descriptions, reviews, and gameplay sessions to catch all necessary details of the inventory. For each game, both reviewers completed a predefined table (see Table II) that followed the general structure of menus (cf. Section II).

Step 3: Open Coding

The results from the previous stage were used to derive the first labels. Using *open coding*, we analyzed the data and generated the first codes describing each inventory's aspects. We unified similar codes into a set of early concepts and categories shared by multiple games. For instance, the code *thematic style* represents an inventory fitting the game's style very closely. Alternatively, other inventories were marked with the code *abstract style* to indicate a neutral user interface that does not reflect the actual theme. The whole process was done by hand in a joint discussion session.

Step 4: Axial and Selective Coding

The resulting codes, concepts, and early categories were discussed in multiple sessions to combine them into logical units. We reassigned the games to new codes, consulted related work, and revisited the games to achieve a universal set of categories named *building blocks*. Each block contained two to four concepts with underlying codes. For instance, all inventories either *preserved* the item's scale or *normalized* the size to fit the structure. These two codes describe the item's *scale* within the inventory and form a concept as part of the general building block *item representation*. The three others are *interface*, *item arrangement*, and *interactions*. Figure 2 depicts the complete process.

V. Results

Based on the related work, developer feedback, and games analysis, this section summarizes the main characteristics of inventory systems in virtual environments. First, we assess the game- and user-related requirements that need to be taken into account when designing an inventory for a particular use case. Afterward, we decompose the structure of inventories into a universal taxonomy by explaining the different building blocks and identified design choices (see Figure 3).

A. Game-Related Requirements

Using an inventory can provide significant benefits to many games. The success of a particular implementation depends on the interplay between the game and the storage feature. Therefore, every design phase should begin with a careful analysis of the use case and the required features.

The key factor determining the design process is the stored item. Usually, items are subdivided into three groups: *”tools, goods, and loot”(**D2**)*. Tools and goods are frequently utilized, whereas loot is mostly used for acquiring wealth. This subdivision leads to two primary inventory types: *Carry* inventories focus on few, quickly accessible items, e.g., in the game *Fortnite* [46]. *Diablo III* [47] is a perfect remedy for a *loot* inventory, providing easily manageable storage [48], [49]. Furthermore, considering the complexity and variety of included items is essential. Games relying on few, diverse objects need different designs than games with large amounts of similar items.

Apart from item considerations, the inventory’s particular purpose is decisive for any design. Fast-paced action games require an efficient layout limiting the features in favor of speed, whereas RPGs may interweave a more complex design with the gameplay, e.g., through *”managing limited storage spaces”(**D12**)*. The game’s target platforms determine the available capabilities: Early mobile HMDs were constrained to rotational controllers, whereas current setups provide positional tracking or the ability to track physical proxies.

B. User-Related Requirements

One reason for failed inventory designs is poor fitting to the game’s characteristics. Many interviewed developers stated that their implementations often *”just did not feel natural”(**D1**)*. This feedback illustrates that designers should focus not only on the structural requirements but also the player experience. The proposed design considerations in this section can help determine whether a particular design fits the special requirements of VR and conveys a proper user experience.

*1) **Comprehensibility**:* The information for every stored item must be displayed in a comprehensible manner. Displaying too many items or meta-information on the limited VR screen can easily lead to visual cluttering [8], [12], which increases the mental effort and can spoil the whole gameplay [49].

*2) **Interactivity**:* Managing and interacting with the inventory and the stored items should be as easy and quick as possible [13]. For instance, situation-dependent controls may simplify the necessary user actions to a minimum. However, such game designs bear the risk of reducing the feeling of agency [49]. Especially in VR, players like to interact with the environment and to feel in control over the resulting actions.

*3) **Contextual Embedding**:* Even the best inventory design will not be well received without matching the enclosing game. An interactive system should always fit the provided context regarding theme and interactivity. A linear story-driven game does not need a fully fetched inventory with categories and sorting methods. Instead, a slot-based storage integrated within the game’s theme fits much better to the limited player abilities.

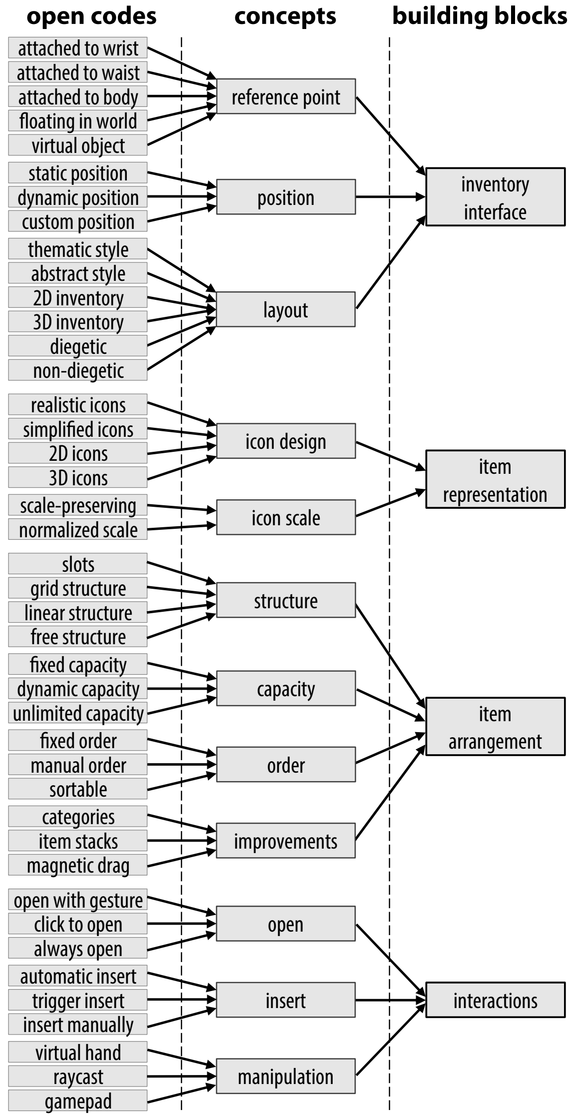

Fig. 2. Grounded theory analysis: The initial observations are formalized into open codes, which are structured into concepts and overall building blocks.

*4) **Personalization**:* Inventories as personal and individual spaces have a considerable impact on the game experience. Especially in linear games, players have little to no chance to individualize their gameplay. The exception is an inventory, which provides complete freedom over content and organization [49]. Thus, freely manageable inventories can provide significant advantages to character identification and presence.

C. Structural Taxonomy

Next, we use the identified concepts from the previous analysis-step to disassemble the inventory into its components. We explain each building block and propose design recommendations based on related research and developer feedback.

*1) **Interface**:* The interface is the fundamental component containing all storage items and determining the inventory’s position, shape, and design. During the invocation, the interface is bound to a reference point used as an initial positional anchor.

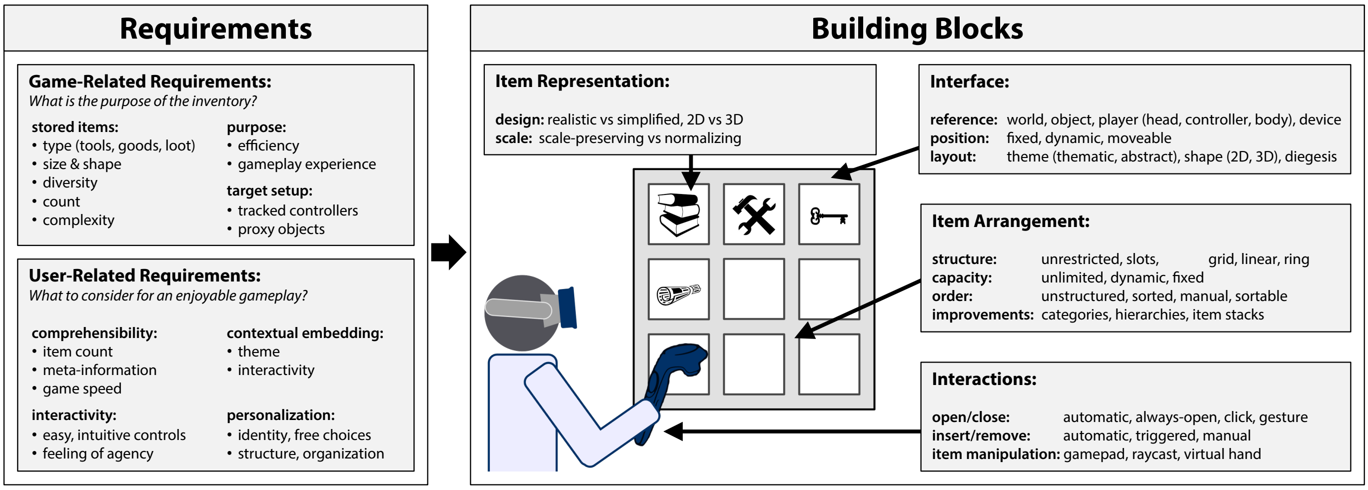

Fig. 3. Requirements and taxonomy of inventory systems in virtual environments. This figure is read from the left, starting with the requirements that should be taken into account before designing inventories. The considerations are used to select the design choices in the taxonomy on the right.

Following the definition given in the related work, possible reference points are world, object, head, body, controller, and device. The chosen reference determines the inventory's initial location. Fixed inventories retain this position until disposal. Alternatively, dynamic interfaces are attached to the reference point and follow all positional changes. Both approaches might cause occlusion effects between surrounding and inventory, which could easily lead to frustration and decreased usability. Therefore, it might be better to give the player the chance to move the storage freely. This feature could also provide further benefits in terms of personalization and interactivity.

Deciding on an interface layout, developers can choose between a 2D or a 3D style. Most analyzed games use a 2D design, which simplifies the development process by using established interactions. However, those interfaces were collectively rejected by all interviewed developers as they are believed to *"severely ruin the immersion and defeat the purpose of VR"*(***D2***). The alternative is a 3D interface providing the basis for more realistic and better integrated implementations.

Apart from the shape, the layout is also determined by the thematic and diegetic fitting. Usually, VR games aim to maximize immersion into the virtual scenery and avoid any thematic cuts. Therefore, matching the inventory's style as closely as possible to the surrounding environment is natural. In contrast, abstract menus offer the advantage of prior knowledge: Most people have already experienced similar storage interfaces and are proficient to a certain degree. Therefore, an abstract design helps to reduce the necessary cognitive load. Diegetic interfaces maximize thematic embedding and become a part of the game world, e.g., as a backpack [24], [31]. A fully diegetic inventory immerses completely into the environment and removes any perceivable cut reducing the player's presence.

*2) **Item Representation**:* Every stored item needs a graphical or textual representation. The chosen concept strongly influences the amount of conveyable information. Many games need to provide more data than the basic item's appearance. Some of the most common item information are category, count, usability, or value. However, the available display area forces developers to reduce the information to a minimum and rely on meaningful representations to convey the details space-effectively. Realistic designs allow for detailed conclusions on the object's shape and physical properties while merging into the virtual scenario. In return, a more simplified style, such as icons or texts, reduces the visual clutter and allows for increased information density. The choice between a 2D and 3D representation is usually based on the interface type and not directly linked to the degree of realism.

One key aspect of the chosen representation is the displayed size: Preserving the object's original scale removes any discrepancy between the item and its representation in the inventory. However, this design choice could quickly fill the limited space with large items and introduce occlusion problems. The alternative is to normalize the item's scale upon insertion.

*3) **Item Arrangement**:* According to the interviewed developers, the item arrangement is at least as vital as the representation. Depending on the use case, the layout should focus on either accessibility, management, or overview of the content. Most of the analyzed VR games use grids or fixed purpose slots. Few games grant more freedom to the player and support free object placement. Despite providing benefits for presence and personalization, this decision bears the risk of producing obstructive and chaotic inventories. Apart from the item arrangement, other reasons for poor comprehensibility are massive storage sizes or extreme information densities. The typical solutions are limiting the inventory capacity or reducing the provided information per item. Many games mitigate this problem by extending the maximum storage during the journey.

Several inventories provide features to sort the stored items. These range from complete flexibility and self-administered organization, through optional sorting techniques, to fixed automatic orders. After all, inventories should maximize the player's freedom and control over the item arrangement without

Fig. 4. Our three inventory prototypes: *Flat Grid* (left), *Virtual Drawers* (middle), and *Magnetic Surface* (right).

sacrificing too much comprehensibility. The overview can be improved by including concepts such as categories, hierarchies, or item stacks. Some games limit the inventory use to tools and automate the collection and management of loot.

*4) **Interactions**:* The novel VR interaction concepts made possible through spatially tracked controllers are by far the biggest difference compared to non-VR games. Instead of using a simple button click, games could implement more natural ways to open the inventory. An example is *The Gallery* [37], where players reach behind themselves to retrieve a virtual backpack. Interestingly, many examined games do not support opening the inventory but keep it visible. The second major inventory interaction is the item insertion. We identified three approaches: Games require the players to insert items manually or feature automatic or button-triggered collection.

Every inventory requires an interaction technique for item manipulation. The various approaches include classical gamepad controls, raycast-aiming, and physical actions through virtual hands. Direct interactions with tracked controllers require the least learning time and outperform distant object manipulation significantly [50]. Additionally, physical grabbing avoids typical problems of virtual pointers, e.g., Fitt's law [51], and is deemed the gold standard for interactive gameplay. Our results reflect this trend towards more intuitive controls. Only two VR adaptations still rely on the gamepad [20], [33]. A minority of five games use the raycast-aiming, whereas the others prefer the virtual hand. Despite being the most preferred technique, physical grabbing is usually not applicable for games relying heavily on distant object manipulation. The game *The Mage's Tale* [21] tackles this problem creatively by providing a magnetic force ability to drag any item into the own hand.

VI. Designing Inventories

In this section, we assess the practical applicability of our taxonomy by developing three inventories for different use cases (see Figure 4) and explaining the underlying design considerations. We assume that these insights will help practitioners with their design process. As designing an inventory depends largely upon the intended use case, we use our designs to target three different exemplary goals:

1) simplicity and performance
2) natural and intuitive interactions
3) engaging and interactive gameplay

A. Flat Grid – A "Swiss Army Knife"

The prototype aims to be a simplistic and universal interface. It focuses on fast interaction and low visual complexity, useful for fast-paced games requiring efficient item management, e.g., of loot. These demands call for a more abstract and well-known design. As players access it only briefly to place or retrieve an item, it does not need an option to rearrange the positioning. Following these considerations, the interface appears on command at a fixed position in front of the player. An abstract 2D overlay arranging items in a regular grid reduces the visual clutter and makes it easy to scan the contents. Also, the stored items are reduced to simple 2D icons of equal sizes. Finally, we maximize the interaction speed by using a virtual raycast pointer to interact with the stored items.

B. Virtual Drawers – Featuring Natural Interaction

The second design focuses on natural interactions while preserving a clear storage structure. These interactions reduce the necessary learning time and the possibility of misuse, but they usually involve a considerate amount of physical effort and are less suited for huge arsenals of items. Recent VR games have undergone a general shift towards more realistic handling of few meaningful objects. For instance, players use a single upgradable weapon instead of collecting dozens of different arms. Such games can profit from a more natural and intuitive inventory where performance is negligible. Compared to the *Flat Grid*, this use case requires a more realistic interface: A diegetic 3D shelf fits the scenario while preserving the same organized structure. As the original 2D icons no longer fit the 3D interface, we instead scale the stored item to a uniform size. This solution preserves the original shape while accounting for individual size differences. Finally, the design focuses on natural interactions instead of speed. Therefore, the items are stored in the inventory by placing them physically into one of the free slots. The players may also grab the whole inventory using a handle and move it freely within the environment.

C. Magnetic Surface – Inventories as Gameplay Element

The final design demonstrates the use of inventories as a core gameplay element. In games like *Green Hell* [1], players spend much of their playtime arranging the items within their backpack to counter limited carrying capacity. Instead of focussing on performance, such designs aim for innovative experiences. Usually, there is no generic approach as such implementations are highly application specific. For our particular use case, we focus on a novel VR experience offering maximal freedom. Unlike the previous design, this prototype preserves the item's shape and scale, allowing players to distinguish the items based on their shapes and sizes. We replaced the grid with a simple rectangular worktop floating in the air. Players can put any object onto the plate where magnetic force keeps the items in place. Consequently, players are in full control over item arrangement and positioning without any form of forced organization. The inventory does not limit the item density, which provides a dynamic capacity based on the size of the worktop and the player's abilities.

VII. Conclusion

Developers of VR inventories can select from various designs for each component and thus must consider the framing determined by the respective game. Our work introduced this timely topic by structuring the research area in multiple steps. After filtering the applicable, related work, we conducted semi-structured interviews with developers to assess the community's needs. Then, we analyzed the inventories of 18 VR games and decomposed the interfaces' structure. Our taxonomy covers the vast design space of VR inventories, ranging from simple 2D solutions to diegetic interfaces. While these building blocks share common aspects with non-VR inventories, they also account for VR-related peculiarities, such as spatial interactions. Structuring the design process into requirements and building blocks provides a guideline and facilitates decision-making. We emphasize that our work is not limited to real-world inventories but also applies to storage concepts beyond those known from our daily lives. In the final part, we designed three inventories for specific use cases to demonstrate our contribution.

The application section also unveils our open questions: Developers usually consider game- and user-related requirements first. These assumptions provide an idea of the critical aspects required for the next implementation steps. However, how these considerations lead to specific design decisions favorable for the intended use case remains unclear. Next, developers must assemble a complete set of design choices. This selection bears further challenges in the form of detrimental effects between individual design elements. These problems illustrate the need to evaluate the interplay between requirements and design choices and the mutual effects between building blocks further. We assume that such future work will complement our structural approach and help developers and researchers.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put...": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	**The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games** *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

VR Animals: Surreal Body Ownership in Virtual Reality Games

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The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games

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VR Animals: Surreal Body Ownership in Virtual Reality Games

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Abstract
The illusion of being someone else and to perceive a virtual body as our own is one of the strengths of virtual reality setups. Past research explored that phenomenon regarding human-like virtual representations. In contrast, our ongoing work focuses on playing VR games in the role of an animal. We present five ways to control three different animals in a VR environment. The controls range from third person companion mode to first person full-body tracking. Our exploratory study indicates that virtual body ownership is also applicable to animals, which paves the way to a number of novel, animal-centered game mechanics. Based on interview outcomes, we also discuss possible directions for further research regarding non-humanoid VR experiences in digital games.

CCS Concepts
•Human-centered computing → Virtual reality; •Software and its engineering → Interactive games; Virtual worlds software;

Author Keywords
Virtual body ownership; body transfer illusion; animal avatar control; animal embodiment; virtual reality games.

Figure 1: Avatars of our study.

Figure 2: Tiger control in the full body tracking (FB) mode: arm = forepaw, leg = hindpaw.

Figure 3: FB spider: arm = front limb, leg = three hindlimbs.

Introduction

Who do we want to be in a game? Sorcerer, rogue, or warrior, these are default roles most gamers would think of. Even when a game offers more exotic choices for our avatar, we usually still get a humanoid representation. Some successful games allow players to at least partly identify with realistic, non-humanoid avatars. For example, *Black & White* [18] incorporated bipedal animals, *Gothic 2* [25] allowed players to transform into wild animals like wolves and scavengers to prevent fights or complete quests, and *Deadly Creatures* [26] offered combat experiences vs. other animals while being a tarantula or a scorpion. And although players seemed to enjoy such non-humanoid mechanics, playable, realistic animals remain a rarity in common digital games, not to mention VR titles.

Our claim is that incorporating animals as player avatars into VR has the potential to unveil a set of novel game mechanics and maybe even lead to a "beastly" VR game genre. Our claim is based on two assumptions. First, VR exposes the phenomenon of virtual body ownership (VBO) [36]. We suppose that VBO is transferable to non-humanoid characters, e.g., it is possible to experience the feeling of being in an animal body while playing a VR game. We suggest that such a feeling might be an interesting player experience worth further study. Second, utilizing the abilities of animals such as flying as a bird or crawling as a spider could be significantly more engaging in VR due to the increased presence compared to non-VR games.

Hence, our first step into this direction was to explore whether and how VBO applies to animals in VR. We also researched how players could control their representation in such games, as there often is no straightforward mapping between human and animal postures. Therefore, we have implemented two first person and three third person control modes for three different animals. We evaluated our mechanisms in an exploratory survey with eight participants. In addition, we repeated parts of the study with two children, as we were curious regarding their VBO experiences and potential differences compared to adults. Our results indicate that VBO is indeed noticeable even with non-humanoid models, and the interview outcomes expose the general interest of participants regarding playing as animals with the respective set of virtual skills.

The contribution of our work in progress report is twofold. Backed by our evaluation, we propose several possibilities how animal avatars could be controlled in VR and what advantages and disadvantages such modes could have. Furthermore, our paper describes a number of possible future experiments that we think are helpful to better understand the VBO phenomenon in VR games and to establish animal control as an engaging game mechanic.

Related Work

Our work can be classified as research in the areas of VBO and player experience in VR. We assume that the latter concepts are familiar to our community, hence we only briefly address them before going into detail regarding VBO. Player experience [43] refers to aspects such as challenge, competence, immersion, and flow. The process of measuring such components was described by, e.g., IJsselsteijn et al. [12, 13] and sublimed into the Game Experience Questionnaire [14].

Playing in a VR setup adds *immersion* [5] as an influential factor. As often done by researchers (cf. [2, 31]), we refer to immersion as the technical quality of a VR equipment and use the term *presence* [37, 33] when talking about the influence of such equipment on our perception. Several ways to measure presence were exposed by, e.g., Lombard et

Figure 4: Human FB mode.

Figure 5: FB bat: arm = wing, leg = claw.

Figure 6: Player perspective: looking in a mirror in HB mode.

al. [19] and IJsselsteijn et al. [15]. Apart from presence, i.e., the feeling of being there [11], immersive setups are capable of inducing the illusion of virtual body ownership, also referred to as body transfer illusion, agency, or embodiment.

Virtual Body Ownership

One of the pioneering works regarding VBO was conducted by Botvinick et al. [3]. The authors detected the so-called rubber hand illusion in an experiment where they hid the real arm of the participant behind a screen that displayed an artificial rubber limb. Both the real and virtual arms were then simultaneously stroked by a brush and participants reported to sense the touch on the virtual rubber hand. Further studies by Tsakiris et al. [41, 40] revisited the rubber hand illusion and established a first neurocognitive model that described (virtual) body ownership as an interplay between multisensory input and internal models of the body. As a follow-up to virtual arms, researchers also extended the experiments to a whole body representation [8, 24, 17]. These early findings were followed by a number of insights regarding the visuotactile correlation [34, 30] and the involved visuoproprioceptive cues [35, 23, 21, 36] that help us to enhance the VBO illusion. We will not go into more detail at that point, as the mentioned works focus on anthropomorphic representations and, thus, we cannot assume that the same principles are also applicable for animals.

More related to our research, Lugrin et al. [20] varied the level of anthropomorphism in their experiments and stated that VBO is also noticeable with non-humanoid characters. Researchers have determined that adding virtual body parts does not necessarily destroy the VBO illusion. For instance, Guterstam et al. [10] experimented with a third arm that evoked a duplicate touch feeling, while Normand et al. [22] rather focused on creating the illusion of having an enlarged belly. Won et al. [44] further analyzed our ability to inhabit non-humanoid avatars with additional body parts.

Even more interesting for VR games, Steptoe et al. [38] added a tail-like, controllable body part to the avatar representation. The authors concluded that the tail movements need to be synchronized to provide a higher degree of body ownership. Another prominent example of body modification that could be promising for VR games are virtual wings. In that area, Egeberg et al. [7] exposed several ways how wing control could be coupled with sensory feedback, and Sikström et al. [32] assessed the influence of sound on VBO in such scenarios. Regarding realistic avatars, Waltemate et al. [42] showed that customizable representations lead to significantly higher VBO effects.

As a final remark regarding VBO experience, we point readers to the recent work in progress by Roth et al. [29]. In particular, the paper presented a VBO questionnaire based on a fake mirror scenario study. The authors suggested to measure acceptance, control, and change as the three factors that determine VBO. In our experiments, we applied the proposed questionnaire as we were curious to see how it performs for animal avatars.

There is a body of literature related to the control of animal avatars that should be mentioned in this context. Leite et al. [16] experimented with virtual silhouettes of animals that were used like shadow puppets and controlled by body motion. For 3D cases, Rhodin et al. [27] applied sparse correspondence methods to create a mapping between player movements and animal behavior and tested their approach with species such as spiders and horses. As a next step, Rhodin at al. [28] experimented with the generalization of wave gestures to create control possibilities for, e.g., caterpillar crawling movements. Our research extends those methods by presenting additional mechanisms tailored to animal avatar control.

Control Modes

FPM = First Person Mode
TPM = Third Person Mode

FB: *Full Body (FPM).* Player posture is mapped to the whole virtual body. Mapping depends on the animal, see Figures 2-5 for details.

HB: *Half Body (FPM).* Lower body mapped to all limbs of an animal, e.g., moving the left leg triggers movements of the two left limbs of a tiger. Compared to FB, players remain in an upright posture for tiger and spider.

3CAM: *Avatar Sticks to Cam (TPM).* The avatar is in front of the player (cf. Figure 12) and translated in sync upon player movement or rotation. A default walking animation is applied and the avatar always looks forward.

3NAV: *Agent Navigation (TPM).* Similar to 3CAM, but avatar walks towards the target on its own, leading to a more natural movement and rotation.

3FOL: *Cam Follows Avatar (TPM).* Default TPM known from non-VR games. Player "is a cam" that follows the avatar. Player rotation triggers cam translation and rotation around the avatar.

Controlling Animal Avatars in VR

As we can see from related work, body ownership requires as much sensory feedback as possible. Hence, if we want to evoke such experiences in a VR game, a simple gamepad control is probably not adequate. Another well-established mechanism is to map player posture to the virtual representation. This is a challenging task, as most animals are not bipedal and there is no straightforward posture mapping.

We focused on three example animals (tiger, bat, spider) to cover a broad range of possible avatars as shown in Figure 1. Tigers expose a similar skeleton and similar limb proportions compared to humanoids. Bats have a similar skeleton, but very different proportions. Finally, spiders have a completely different skeleton and an increased number of limbs with non-human proportions.

We utilized a combination of Unity3D [39] and HTC Vive [6] including additional Vive trackers to implement five different control mechanisms for these animals. These modes are summarized on the left side. As we relied on the same testbed scene for all conditions, animals were scaled to roughly equal, human-like dimensions. Inspired by Debarba et al. [9], we experimented with first and third person modes. For simplicity, we refer to them as *FPM* and *TPM*. From literature, we know that FPM are superior regarding VBO, but come with the disadvantage that players cannot see their whole virtual body if there are no reflective surfaces such as mirrors. Hence, we decided to integrate a wall-sized mirror into our testbed as shown in Figure 6.

For two FPM, we implemented iterative and closed-form inverse kinematics (IK) [4] solvers to project player postures on the animal skeleton, which then deformed the skinned mesh of the virtual avatar. For more stable IK results, we equipped our players with three additional vive trackers that were mounted on the back and ankles.

Exploratory Study

The goal of our experiment was to gather knowledge regarding the VBO phenomenon applied to animal avatars. In addition, we wanted to explore how potential players perceive the different control modes and what they like or dislike about our animal avatars in VR.

Procedure

We conducted a within-subjects study in our VR lab and tested the following conditions: FB human (as reference for VBO), FB spider, FB tiger, FB bat, HB spider, HB tiger, 3CAM spider, 3NAV spider, and 3FOL spider. We excluded the HB bat case, as that animal can be controlled in an upright pose in FB. Thus, we do not see any advantages of using the lower body only. We limited the three TPM to one animal, as these modes expose the same behavior for all three animals.

For each condition, we told the participants to move around in the virtual arena and experiment with their virtual representation. For instance, subjects were able to move and drag various objects such as crates, pylons, and tires. Subjects stayed in the virtual world for around five minutes for each condition, which is, according to literature, enough to experience VBO effects. After each condition, we administered the alpha VBO questionnaire by Roth et al. [29] with a number of additional custom questions related to avatar control. Answers were captured on a 7 point Likert Scale ranging from 0 (*totally disagree*) to 6 (*totally agree*).

In addition to the questionnaire, we conducted semi-structured interviews after each control mode, i.e., five interviews in total. In particular, we asked subjects what they liked best/least and why, whether they could imagine such controls in a game, and how we could further enhance that mode. Upon completion of all conditions, participants had the chance to provide general feedback regarding animal

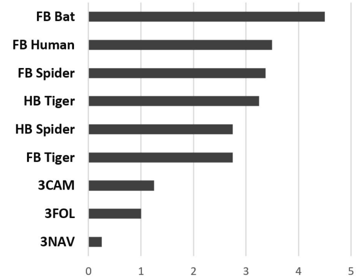

Figure 8: Means for: *I felt as if the body I saw in the virtual mirror might be my body.*

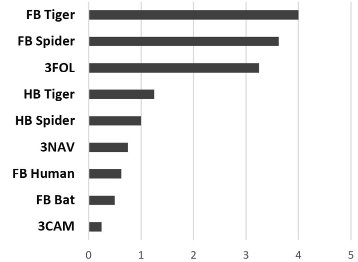

Figure 9: Means for: *The controls exhausted me [custom].*

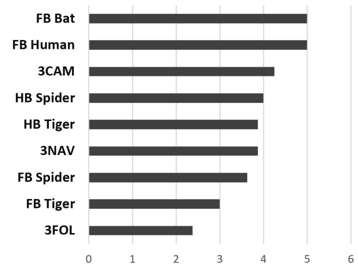

Figure 10: Means for: *I could imagine such controls in a game [custom].*

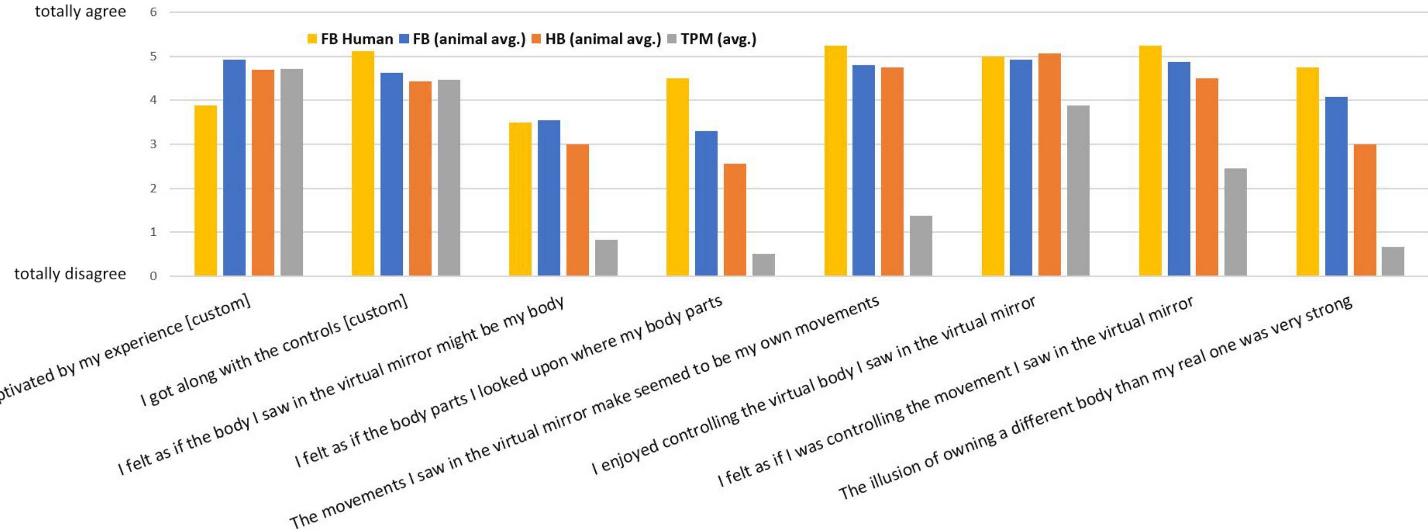

Figure 7: Mean values for our custom and most alpha IVBO questions. TPM is computed as an average from 3CAM, 3NAV, and 3FOL.

avatars and tell us their favorite animals to be included in the next experiments.

Results and Discussion

Overall, 8 adults (2 female) participated in our study with a mean age of 29.5 ($SD = 6.38$). In addition, we had two children participators aged 8 and 10, however, we will address them in a separate section. All participants reported playing digital games at least a few times a month, and all had used VR gaming systems before.

The results depicted in Figure 7 and Figure 8 indicate that FB and HB control modes can indeed create the illusion of owning an animal body in VR. Both modes did not perform notably worse than the reference virtual human and, as expected, outperform all three TPM. Note that there are no big differences regarding VBO when comparing FB and HB, which was a surprising observation because HB reflects only half of our posture changes.

As can be seen in Figure 9, subjects perceived FB modes for spider and tiger control as rather exhaustive because they had to kneel and crouch on a yoga mat. For such type of animals, HB modes seem to be more promising, as they expose the same amount of VBO without being aggravating. However, one disadvantage of HB is the less direct mapping, i.e., subjects *"felt limited regarding possible interactions as it is difficult to forecast the avatar behavior sometimes"(**P2**)*. Regarding missing control in HB, two participants mentioned that, in case of a spider, they would like *"to control each limb separately, maybe even with finger movements"(**P5**)*.

Participants explained that the bat (FB) was their favorite: *"The bat behaved exactly how I expected and it was intriguing to precisely control my wing movements because it appeared realistic to me"(**P7**)*. Subjects often expressed their desire to utilize the flying capability: *"I could feel more like a giant bat if I could fly by moving my arms and maybe lean forward to accelerate"(**P4**)*.

Figure 11: Player perspective: avatar behavior in 3NAV mode when player walks backward.

Another finding to be mentioned is the different perception of FB spider and FB tiger modes. Participants reported that the tiger felt less engaging, and we recorded several similar statements such as the following: *"the forepaws were too short, they even felt shorter than my real arms and I could not do much with them"(**P2**)*. Of course, tiger paws are not shorter, but the tiger head position leads to such a distorted perspective. Hence, we suppose that perceiving virtual limbs as shorter than our real limbs feels rather limiting, whereas longer virtual limbs are rather classified as useful tools that enhance our interaction space in VR.

Figure 12: Player perspective: spider in 3CAM mode.

In all three TPM, the measured VBO effects were rather low compared to FPM. Most participants reported to slightly prefer the 3CAM mode over 3NAV. In the 3NAV condition, subjects perceived the avatar to be *"controlled telepathically"(**P8**)* and to *"orbit the player"(**P2**)*. One participant was slightly surprised at one point (similar to Figure 11): *"when I walked backward, the spider suddenly looked at me and seemed to chase me"(**P1**)*. We suggest that 3CAM and 3NAV are both suited for games (cf. Figure 10), yet 3NAV resembles more a companion-like behavior rather than an avatar representation. In contrast, we do not recommend the usage of 3FOL mode, as it is capable of evoking dizziness, as was confirmed by two participants. Especially regarding the question about how exhausting the control was, 3FOL performed notably worse compared to 3CAM and 3NAV as depicted in Figure 9.

We also recorded a wish list of animals that subjects would like to control: birds, elephants, bunnies, fishes, slugs, apes, dinosaurs, and sharks. Furthermore, one participant requested a mapping of facial expressions.

Children and Animal Avatars

Both children answered to most VBO-related questions with 6 (*totally agree*). This could be an indicator that children might be more affected by such VR phenomena and we suggest follow-up research in that direction. In contrast, both TPM were perceived as least exciting, even if one *"could see lots of details of the animal"(**P10**)*.

Conclusion and Future Work

Our ongoing research revealed strong indications that the illusion of virtual body ownership is applicable to animal avatars. We suggest that integrating such avatars in VR games paves the way for interesting game mechanics, as the participants of our study expressed excitement about the possibility to play as an animal. We also exposed different possibilities to map player postures to virtual representations and observed that a half body tracking mode might be a valuable trade-off between comfort and VBO.

Therefore, we suggest to examine such half body projections in more depth to find a sweet spot for emerging VR games. Furthermore, we are going to evaluate such animal controls in a complex VR scenario with realistic objectives and meaningful interactions. As desired by the majority of participants, we propose to enhance the virtual representations with appropriate capabilities such as flying to further enhance the VBO effect. Finally, we argue that animal VBO might be a method to increase our empathy regarding animals and nature in general [1] or even help against fears such as arachnophobia and suggest further investigations of these claims.

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***Abstract*—Virtual reality offers the unique possibility to experience a virtual representation as our own body. In contrast to previous research that predominantly studied this phenomenon for humanoid avatars, our work focuses on virtual animals. In this paper, we discuss different body tracking approaches to control creatures such as spiders or bats and the respective virtual body ownership effects. Our empirical results demonstrate that virtual body ownership is also applicable for nonhumanoids and can even outperform human-like avatars in certain cases. An additional survey confirms the general interest of people in creating such experiences and allows us to initiate a broad discussion regarding the applicability of animal embodiment for educational and entertainment purposes.**

***Index Terms*—virtual reality, animal avatars, embodiment**

I. Introduction

Due to the depth of immersion, VR setups often excel at creating a strong bond between users and their virtual representations, the so-called avatars. That bond can be strong enough such that we start perceiving the avatar model as our own body—a phenomenon also known as the illusion of virtual body ownership (IVBO) [1]. Previous research agrees that VR is an efficient setup to induce IVBO experiences [1]–[3]. However, the investigated scenarios have been centered mostly around humanoid avatars. Our paper aims at generalizing the IVBO discussion by considering virtual animals as candidates for an embodiment experience.

To provide a starting ground for future research regarding animal embodiment in VR, our work addresses the following question: *Is IVBO applicable to nonhumanoid avatars, and, if so, what potential does that phenomenon have for VR applications and games in particular?*

The primary contribution of our paper is the dedicated research of animal body ownership. Although prior work examined aspects such as the inclusion of additional limbs, tails, or wings, the question whether and how well we can embody virtual creatures remained unanswered. Our work provides a strong evidence that animal avatars can keep up and even outperform humanoid representations regarding IVBO. In our evaluation ($N = 26$), we included a diversified set of animals to account for upright/flying species (bat), four-legged mammals (tiger), and arthropods (spider). Our experiment shows that even spiders (cf. Figure 1), despite having a skeleton that significantly differs from ours, offer a similar degree of IVBO compared to humanoid avatars. Apart from the general assessment of IVBO, our paper proposes and discusses practical approaches to implement animal avatar control[1] by, e.g., half-body tracking for non-upright avatars to reduce fatigue from crouching. We believe that our findings pave the way to the construction of a zoological IVBO framework in the future.

Our additional contribution is a discussion about the potential of VR animals. We conducted an online survey ($N = 37$) that underpins the general interest of people in experiencing virtual animals—be it in educational documentaries or as protagonists in VR games. This survey supports our claim that VR has a potential regarding animal embodiment, resulting in application possibilities for a number of HCI areas such as games research.

II. Motivation

Who do we want to be in a game? Sorcerer, rogue, or warrior–these are default roles most gamers would think of. Even when a game offers more exotic choices for our avatar, we usually still get a humanoid representation. Thus, playable, realistic animals remain a rarity in common digital games, not to mention VR titles with only few exceptions such as *Eagle Flight* [4]. In our opinion, incorporating animals as player avatars into VR has the potential to unveil a set of novel game mechanics and maybe even lead to a "beastly" VR game genre. Furthermore, utilizing the abilities of animals such as flying as a bird or crawling as a spider could be significantly more engaging in VR due to the increased presence compared to non-VR games. Apart from entertainment, we suggest that embodying animal avatars could help us to better understand the behavior of a certain creature, e.g., in an educational documentary, and also increase our involvement with environmental issues [5].

To capture the perspective of our society regarding these outlined applications, we administered an online survey with three sections: VR animals in general, animals in VR documentaries, and animals in VR games. Each section consisted of five questions about participants' experiences in that category and their general interest to give such a scenario a try. The

[1] supplementary video showcasing avatar controls: http://bit.ly/vranimals-cog

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questions were either yes/no, or on a 7-point Likert Scale ranging from 0 (*totally disagree*) to 6 (*totally agree*).

Thirty-seven subjects (21 female), aged 19 to 43 ($M = 26.43, SD = 5.67$), participated in the survey. Overall, 26 of the participants had prior experiences with VR, and 17 of them had already seen an animal in VR. However, only six subjects reported that they had had the chance to control a virtual animal. Our results indicate that the overall interest to try a VR application where animals play an important role is rather high ($M = 5.14, SD = 1.00$), and that subjects would like to observe, interact, and embody VR creatures (all $M > 4.50$).

Participants were keen on trying a VR game with an animal avatar ($M = 4.81, SD = 1.45$). Playing in third-person perspective ($M = 3.65, SD = 1.86$) was preferred less than in first-person ($M = 4.38, SD = 1.66$). However, a paired-samples t-test shows that these differences are not significant. The majority (33) had never seen a VR documentary about animals, but they said would like to try it ($M = 4.70, SD = 1.45$) and even embody a creature in such a documentary ($M = 4.24, SD = 1.80$). Participants also mostly agreed that embodying an animal might help them to better understand the animal's behavior ($M = 4.57, SD = 1.59$) and to increase their empathy toward that creature ($M = 4.89, SD = 1.45$).

Finally, the survey provided a multiple choice question as an opportunity for the subjects to tell us which animals they would like to experience in VR. The top three creature types were flying animals (birds, bats, etc.) with 32 votes, followed by typical mammals (lions, tigers, cats, dogs, etc.) with 30 votes, and by sea animals (dolphins, sharks, whales, etc.) with 25 votes. Combined with the results from our main IVBO study, we suppose that flying creatures indeed have the largest potential to fascinate users as embodiment targets in VR.

III. Related Work on IVBO

Immersive setups are capable of inducing the illusion of virtual body ownership (IVBO), also referred to as body transfer illusion, agency, or embodiment. IVBO [6] is an adaption of the effect of body ownership (BO), a term coined by Botvinick et al. [7]. The authors conducted an experiment to induce the so-called rubber hand illusion, in which they hid the participant's real arm and replaced it with an artificial rubber limb. Both arms were then simultaneously stroked by a brush, which produced the illusion of owning the artificial arm. This effect has gained great publicity and was further researched by Tsakiris et al. [8]. These results eventually led to the first neurocognitive model regarding body ownership [9], which emphasized the interplay between external sensory stimuli and the internal model of our own body. Additional studies extended these finding to other limbs and whole-body representations [10]–[12].

The effect of BO was initially transferred to virtual environments for arms by Slater et al. [13] and entire bodies by Banakou et al. [14]. However, these early studies used the original visuotactile stimulation introduced by Botvinick et al. [7]. Later research introduced sensorimotor cues, i.e., the tracking of hand and finger movement [15], which was reported to be more important than visuotactile cues [1]. This finding is essential for VR setups as it releases possible experiments from the need for tactile stimulations. Furthermore, these two types of different cues are completed by the so-called visuoproprioceptive cues. These cues are a series of different body representations and include subdimensions such as perspective, body continuity, posture and alignment, appearance, and realism. These different subdimensions are listed in the correct order of influence on the effect of IVBO [1], [2], [16], [17], and together are sufficient for inducing the illusion of body ownership [17]. Moreover, Maselli et al. [17] reported the necessity of a first-person perspective. In sum, IVBO is induced by correct visuoproprioceptive cues. Misalignments and visual errors can be compensated for through the weaker aspects of sensorimotor and visuotactile cues. However, this effect can be observed with anthropomorphic characters as well as realistic representations [6], [18], [19].

Fig. 1. Two of our avatars in first-person (top) and third-person (bottom) modes in front of a wall-sized mirror.

Riva et al. [20] illustrated the current interest in significantly altering the morphology of our virtual representation by the following question: *But what if, instead of simply extending our morphology, a person could become something else- a bat perhaps or an animal so far removed from the human that it does not even have the same kind of skeleton— an invertebrate, like a lobster?* Especially for animals that have few characteristics in common with our human body, the approach of sensory substitution [21] is also a promising direction for IVBO research. For instance, we could replace the echolocation feature of a bat by visual or even tactile feedback in VR.

Recently, researchers have studied adapting and augmenting human bodies in VR. Kilteni et al. [22] stretched the virtual arm up to four times its original length and were still able to confirm IVBO. These findings are in line with the work of Blom et al. [23], who reported that a strong spatial coincidence of real and virtual body part is not necessary for the illusion. Furthermore, researchers have determined that additional body parts are not necessarily destroying IVBO. Instead, it is possible to add a third arm and induce a double-touch feeling [24], [25].

Apart from additional arms, other body parts have also been added successfully: Steptoe et al. [26] reported effects of IVBO upon attaching a virtual tail-like body extension to the user's virtual character. The authors further discovered higher degrees of body ownership when synchronizing the tail movement with the real body. Another prominent example of body modification that could be relevant for embodying flying animals is virtual wings. In that area, Egeberg et al. [27] proposed several ways to couple wing control with sensory feedback. Won et al. [28] further analyzed our ability to inhabit nonhumanoid avatars with additional body parts. Regarding realistic avatars, Waltemate et al. [3] showed that customizable representations lead to significantly higher IVBO effects.

Strong effects of body ownership can produce multiple changes in the feeling or behavior of the user [29], resembling the Proteus Effect by Yee et al. [30]. For instance, Peck et al. [31] reported a significant reduction in racial bias when playing a black character. Additionally, virtual race can also affect the drumming style when playing virtual drums [32]. Other reactions are more childish feelings arising from child bodies [14] or greater perceived stability due to a robotic self [33]. These findings demonstrate that IVBO is not just a one-way street but can be used to evoke specific feelings and attributes and possibly also change self-perception.

We point readers to the recent work in progress by Roth et al. [34] regarding IVBO experience. In particular, the paper presented a IVBO questionnaire based on a fake mirror scenario study. The authors suggested acceptance, control, and change as the three factors that determine IVBO. In our experiments, we administered the proposed questionnaire as we were curious to see how it performs for animal avatars. Our research follows up on the works-in-progress paper by Krekhov et al. [35]. The authors conducted a preliminary study with eight participants, and, by applying the alpha IVBO questionnaire [34], concluded that IVBO might indeed work for animal avatars. We significantly extend that apparatus to gather more insights and to produce reliable results, and also to introduce additional surveys about virtual animals to explore the overall benefits of such research.

IV. Animal Embodiment

As we can see from related work, body ownership requires as much sensory feedback as possible. Hence, if we want to evoke such experiences in a VR application, a simple gamepad control is probably not adequate.Prior research has shown that either proprioceptive cues or sensorimotor cues are necessary to induce proper levels of VBO. However, providing such cues is challenging for nonhuman characters as usually no straightforward control mapping exists between the participant and the virtual creature.

In contrast to humans, animals come in various shapes, postures, and types, which makes it difficult to design a universal solution for avatar control. Therefore, our experiment includes multiple models combined with different types of control to gather diverse insights into animal embodiment.

Animal and human bodies differ in three main subdomains that are critical for successful body ownership: skeleton, posture, and shape, as can be seen in Figure 2. Certain animals, such as bats, share a human posture and skeleton but use scaled arms or legs and therefore vary in the natural shape, i.e., differ in terms of proportions. Other creatures such as tigers or dogs have an almost human skeleton, including the same number of limbs. However, they differ in the natural posture by walking on all fours. Finally, other species show a completely different skeleton and differ in the limb count. An appropriate example is a spider, which has eight legs attached to its head segment. To cover these different degrees of anthropomorphism, we have chosen tigers, spiders, and bats as our testbed species. In addition, we added a human avatar to compare our results with humanoid IVBO scores.

A. Mapping Approaches

We designed and evaluated multiple control modes and mapping approaches, as summarized in Table I. Even though prior work, e.g., by Debarba et al. [36], underpins the superiority of first-person mappings regarding IVBO, that finding has not yet been confirmed for nonhuman embodiment. Hence, we decided to use both first-person and third-person perspectives (cf. Figure 1) in our experiment to contribute to the perspective discussion.

The third-person perspective provides the advantage that subjects see their avatars standing right in front of them. However, that perspective is challenging when subjects rotate around themselves. For instance, in current non-VR games, the camera—or, in our case, the player—slides around the avatar to maintain the over-the-shoulder viewport. This approach has been tested as one possible mode and named 3FOL. Another option is to use the subject as the rotational center and turn the animal around (3CAM). This mode is proposed to induce less cybersickness [37] but lacks realism as the avatar slides sideways around the subject. Finally, this approach can be changed to enhance the visual quality by implementing a loose coupling: the animal avatar would be controlled by an agent trying to stay in front of the subject. This concept has the advantage that movement and rotation are chosen optimally to look natural while preserving the rotational center of 3CAM. We refer to this approach as 3NAV. In contrast to these three third-person perspectives, the first-person perspective is not affected by different rotational centers because the subject and the avatar share the same position.

Apart from different perspectives, our approaches also differ in the type of mapping that is applied. The tiger is usually walking on all fours. Hence, a subject imitating and becoming the animal could move the same with all four limbs being mapped to the tiger body. However, this full-body (FB) tracking is assumed to be somewhat exhausting as it forces participants

TABLE I
EVALUATED CONTROL MODES FOR VIRTUAL ANIMALS.

Mode	Evaluated avatars	Description
first-person perspectives:		
full body **(FB)**	human, bat, spider, tiger	User's posture is mapped to the whole virtual body (cf. Figure 2. Mapping depends on the animal; see Figure 2 for examples.
half body **(HB)**	spider, tiger	User's legs mapped to all limbs of an animal.
third-person perspectives:		
user centered **(3CAM)**	spider	The animated avatar is locked into a position in front of the user.
agent controlled **(3NAV)**	spider	The avatar is an autonomous agent following a target in front of the user.
avatar centered **(3FOL)**	spider	The user is rotated around the animated avatar when turning.

to crouch on the floor. As an alternative, we introduce half-body (HB) tracking : the subjects stand or walk in an upright position, watch through the eyes of their animal, and have their lower body mapped to all of the animal's limbs. For instance, in case of a tiger, one human leg corresponds to two of the animal's pawns. This variation preserves the amount of sensory feedback while reducing the necessary physical effort. Another approach—the one we used for the third-person perspectives—is to avoid posture tracking and replace it with predefined avatar animations, only keeping the subject's position and orientation in sync.

B. Testbed Scenario

We utilized a combination of Unity3D and HTC Vive, including additional Vive trackers positioned at the hip and both ankles to enable full-body positional tracking. The HB and FB modes required custom avatar poses depending on tracker positions and rotations. Therefore, we experimented with different approaches based on inverse kinematics (IK) [38]. Physical models typically used for ragdoll systems and iterative solvers tended to jitter and flicker upon combining them with the VR tracking. As these issues were partially caused by unavoidable tracking errors, these approaches did not suit the situation. Instead, we applied a combination of closed-form and iterative solvers to achieve more stability at the cost of limited rotational movement.

As depicted in Figure 3, we placed our experiment in a stereotypical zoo where the participants were locked inside an arena-like cage filled with different interactive items such as cans, crates, or tires. Moreover, we installed a virtual wall-sized mirror to enhance the VBO illusion [39]. So we relied on the same testbed scene for all conditions, animals were scaled to roughly equal, human-like dimensions.

C. Hypotheses and Research Questions

Our main goal is to explore animal embodiment by evaluating the five proposed mapping approaches with different animals. We want to see how potential users perceive the different control modes and what they like or dislike about our animal avatars in VR. Furthermore, we hypothesize that, similar to humanoid IVBO findings [36], third-person modes for animals are inferior to the first-person perspective. To summarize, our questions and hypotheses are the following:

- RQ1: How do first-person modes (FB and HB) for animals perform regarding IVBO compared to a human avatar?
- RQ2: Do our creature types differ regarding IVBO and user valuation?
- RQ3: Is there any difference between FB and HB for the same animal?
- H1: First-person modes significantly outperform third-person modes regarding induced IVBO.

D. Procedure and Applied Measures

We conducted a within-subjects study in our VR lab and tested the following conditions: FB human (as reference for IVBO), FB spider, FB tiger, FB bat, HB spider, HB tiger, 3CAM spider, 3NAV spider, and 3FOL spider. We excluded the HB bat case because that animal can be controlled in an upright pose in FB. Thus, we do not see any advantage to using the lower body only. We limited the third-person modes to one animal because these approaches behave the same for all animals.

Upon the participants' arrival, we administered a general questionnaire assessing age, gender, digital gaming behavior, and prior experiences with VR systems. For each condition, we told the participants to move around in the virtual arena and experiment with their virtual representation. For instance, subjects were able to move and drag various objects, such as crates, pylons, and tires. Subjects stayed in the virtual world for around five minutes for each condition. This duration is a typical choice for IVBO studies [8] despite the finding that even 15 seconds may be enough to induce body ownership [40].

We decided against performing threat tests for capturing IVBO, as the sequence effects in our case would be too significant. Note there is no unified procedure for measuring IVBO and a threat test is not the only possibility [34], [41]. Instead, we decided to use the alpha IVBO questionnaire by Roth et al. [34], and also checked its reliability by calculating Cronbach's alpha for all subscales (all alphas > 0.81).

We administered the alpha IVBO questionnaire after each condition. Answers were captured on a 7-point Likert Scale ranging from 0 (*totally disagree*) to 6 (*totally agree*). In

Fig. 2. Three virtual animals, their controls in FB mode, and the human avatar that was used as the reference for IVBO comparisons. The animals were chosen such that they differ from humanoids in IVBO-critical domains, i.e., shape (bat), skeleton (spider), and posture (tiger, spider).

particular, the questionnaire captures the three dimensions acceptance, control, and change. Acceptance reflects self-attribution and owning of the virtual body by statements such as: *I felt as if the body parts I looked upon were my body parts*. Control mostly focuses on the correct feedback and agency. One example is: *I felt as if I was causing the movement I saw in the virtual mirror*. Finally, change measures self-perception and is usually triggered when the avatar differs much from the user. Three subitems focus on changes during the experiment (e.g., *At a time during the experiment I felt as if my real body changed in its shape, and/or texture*), whereas another three subitems capture after-effects (e.g., *I felt an after-effect as if my body had become taller/smaller*).

We extended the questionnaire by additional custom questions and statements to capture fascination (*The overall experience was fascinating*), ease of control (*I coped with the control of the avatar*), and fatigue (*Controlling the avatar was exhausting*). We used the same scales as for the IVBO questions. Furthermore, we conducted semistructured interviews after each control mode, i.e., after FB, HB, 3CAM, 3NAV, and 3FOL. In particular, we asked subjects what they liked best/least and why, whether they could imagine such controls in a VR game, and how we could further enhance that mode. Upon completion of all conditions, participants had the chance to provide general feedback regarding animal avatars and tell us their favorite animals to be included in the next experiments.

Twenty-six subjects (13 female) with a mean age of 23.46 ($SD = 7.06$) participated in our study. Most participants (21) reported playing digital games at least a few times a month, and the majority (21) had used VR gaming systems.

To address our hypothesis and research questions, we compare all nine conditions regarding their IVBO performance for acceptance, control, and change. All investigated parameters were approximately normally distributed according to Kolmogorov-Smirnov tests. Hence, we used one-way repeated measures ANOVA to compare the measured IVBO values outlined in Figure 4. The outcomes differed significantly in all three dimensions, i.e., acceptance, F (4.86, 122.14) = 18.23, p ¡ .001, control, F (3.64, 90.95) = 18.54, p ¡ .001, and change, F (4.11, 102.73) = 14.54, p ¡ .001. Post hoc Bonferroni tests provided additional insights into these differences:

Acceptance: the human avatar ($M = 2.79, SD = 1.31$) was rated significantly lower than FB bat ($M = 4.33, SD = 1.10$) and HB spider ($M = 3.63, SD = 1.29$) with $p < .01$ in both cases.

Control: FB bat ($M = 5.11, SD = 0.82$) achieved significantly higher scores than all other modes, whereas 3NAV ($M = 2.41, SD = 1.38$) and 3FOL ($M = 2.55, SD = 1.22$) performed significantly worse than each first-person mode (all $p < .05$).

E. Results

Change: All modes had rather low values, as can be seen in Figure 4. FB bat ($M = 2.22, SD = 1.28$) was rated significantly better (all $p < .01$) than HB tiger ($M = 1.57, SD = 1.18$), 3CAM ($M = 1.02, SD = 1.34$), 3NAV ($M = 0.79, SD = 1.10$), and 3FOL ($M = 0.92, SD = 0.90$). Also, all first-person modes significantly outperformed 3NAV and 3FOL (all $p < .05$).

To create a better picture for RQ2, we also considered our custom questions and statements summarized in Figure 5. Our conditions significantly differed regarding fascination, F (3.68, 92.08) = 2.99, p = .026, ease of control, F (5.10, 127.58) = 8.58, p ¡ .001, and fatigue, F (5.43, 135.76) = 13.46, p ¡ .001. Post hoc Bonferroni tests revealed the following details:

Fascination: FB bat ($M = 5.27, SD = 0.78$) significantly outperformed (all $p < .05$) FB human ($M = 4.42, SD = 1.24$),

Fig. 3. We chose a virtual zoo for our testbed scenario. The cage is equipped with a wall-sized mirror to enhance IVBO.

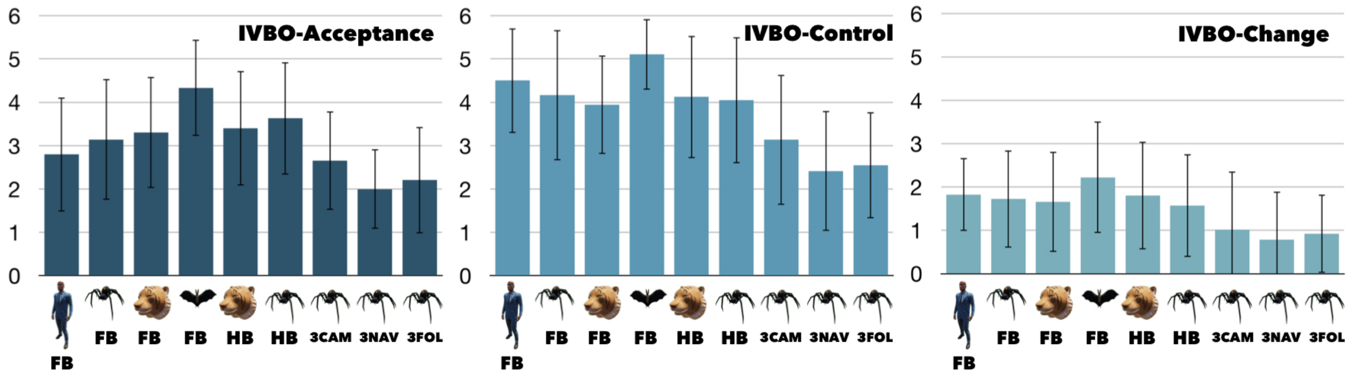

Fig. 4. Mean scores and standard deviations for the three IVBO dimensions: acceptance, control, and change.

HB tiger ($M = 4.08, SD = 1.55$), 3CAM ($M = 4.27, SD = 1.51$) and 3FOL ($M = 3.88, SD = 1.80$).

Ease of Control: Again, FB bat ($M = 5.38, SD = 0.75$) was perceived very positively and had significantly higher scores (all $p < .01$) than all other modes except 3CAM ($M = 4.65, SD = 1.47$), which was ranked second. In contrast, 3FOL ($M = 3.04, SD = 1.71$) produced most control difficulties, which resulted in significantly lower scores (all $p < .05$) than FB human, FB bat, HB spider, and 3CAM.

Fatigue: Similarly, 3FOL ($M = 3.65, SD = 2.00$) was most exhausting and performed significantly worse (all $p < .05$) than all modes except FB tiger ($M = 3.58, SD = 1.39$) and FB spider ($M = 3.35, SD = 1.55$). The two latter modes were also rated significantly inferior (all $p < .05$) to the remaining modes, which all stayed below 2 as mean value.

F. Discussion

*1) How do first-person modes (FB and HB) for animals perform regarding IVBO compared to a human avatar? - **RQ1**:* In all three IVBO dimensions, ANOVA did not reveal any significant advantages of FB human over the animal first-person modes. On the contrary, for acceptance and control, the humanoid representation was significantly outperformed by FB bat, and, for acceptance, also by HB spider. Hence, our main observation is that IVBO should be applicable for nonhumanoid avatars that differ in shape, skeleton, or posture from our human body.

However, we are aware that the appearance of the human avatar has also a strong impact on IVBO. For instance, customizing that representation [3] could produce significantly higher IVBO scores for that condition. Thus, we do not want to exaggerate the generality of our finding, and rather state that animal IVBO has the potential to keep up with humanoid IVBO and, thus, is worth further, more detailed investigations.

*2) Do our creature types differ regarding IVBO and user valuation? - **RQ2**:* In our case, the clear "winner" regarding IVBO scores and our custom questions is the bat, a creature type that mostly differs in shape but maintains similar posture and skeleton compared to our body. This finding might be an indication that animals with human-like, upright postures are more suited for IVBO effects. The quantitative results also align with the interview feedback that we got during the evaluation: *"The bat behaved exactly how I expected and it was intriguing to precisely control my wing movements because it appeared realistic to me"(**P7**).* Subjects often expressed their desire to utilize the flying capability: *"I could feel more like a giant bat if I could fly by moving my arms and maybe lean forward to accelerate"(**P4**).*

Another finding is the different perceptions of FB spider and FB tiger modes. Participants reported that the tiger felt less engaging, and we recorded several similar statements such as the following: *"The forepaws were too short, they even felt shorter than my real arms and I could not do much with them"(**P2**).* Of course, tiger paws are not shorter, but the tiger head position leads to a distorted perspective. Hence, we suppose that perceiving virtual limbs as shorter than our real limbs feels rather limiting, whereas longer virtual limbs are classified as useful tools that enhance our interaction space. This finding would also explain the supremacy of FB bat mode with wings as extended tools: *"The long arms of the bat felt a bit like two long sticks I could use to reach more items"(**P18**).*

*3) Is there any difference between FB and HB for the same animal? - **RQ3**:* Our experiment did not reveal any significant differences in that regard, which is surprising because HB reflects only half of our posture changes. HB spider overall achieved positive ratings that were close to FB bat and even significantly outperformed FB human regarding acceptance.

Our custom question related to fatigue revealed that subjects perceived FB modes for spider and tiger control to be significantly more exhausting than their HB counterparts because they had to kneel and crouch on a yoga mat. For such types of animals, HB modes seem to be more promising because they expose the same amount of IVBO without being aggravating. However, one disadvantage of HB is the less direct mapping, i.e., subjects *"felt limited regarding possible interactions as it is difficult to forecast the avatar behavior sometimes"(**P2**).* Regarding missing control in HB, two participants mentioned that, in case of a spider, they would like *"to control each limb separately, maybe even with finger movements"(**P5**).*

*4) First-person modes (FB and HB) significantly outperform third-person modes (3CAM, 3NAV, 3FOL) regarding induced IVBO - **H1**:* Overall, all third-person modes achieved rather

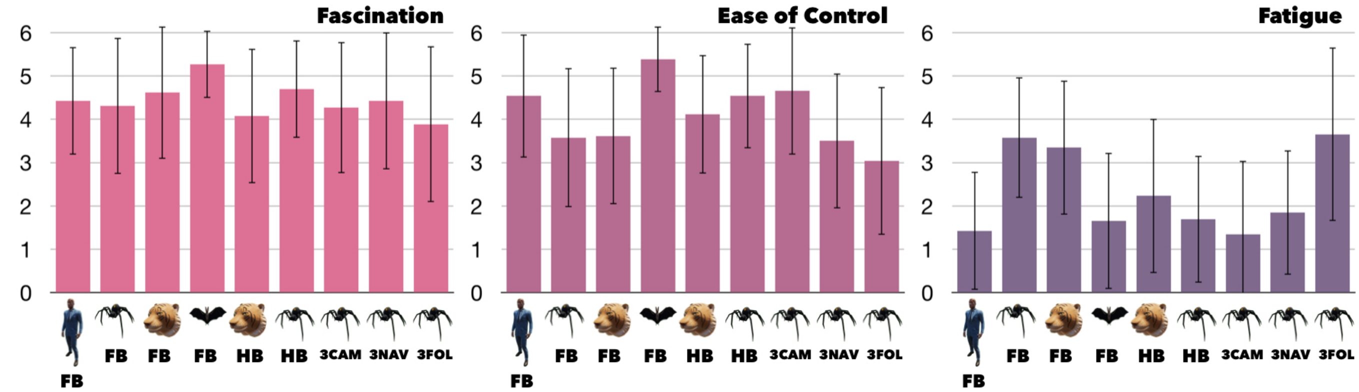

Fig. 5. Mean scores and standard deviations for fascination (*The overall experience was fascinating*), ease of control (*I coped with the control of the avatar*), and fatigue (*Controlling the avatar was exhausting*).

low scores in all IVBO dimensions. In particular, for control and change, the 3NAV and 3FOL modes were significantly outperformed by all first-person perspectives, which mostly supports our hypothesis and is in line with humanoid research [17], [36]. Hence, if a higher IVBO is desired, controlling an animal in first-person mode is advantageous.

The scores for 3CAM were not significantly lower compared to first-person modes, which renders that approach a viable alternative if first-person is not possible. In the interview, most subjects reported slightly preferring the 3CAM mode over 3NAV and 3FOL. In the 3NAV condition, subjects perceived the avatar to be *"controlled telepathically"(**P8**)* and to *"orbit the player"(**P2**)*. One participant was surprised at one point (cf. Figure 6): *"When I walked backward, the spider suddenly looked at me and seemed to chase me"(**P1**)*. We suggest that 3CAM and 3NAV are both suited for VR applications, yet 3NAV resembles more companion-like behavior rather than an avatar representation. We do not recommend using the 3FOL mode, as it is capable of evoking dizziness, as was confirmed by two participants. Especially regarding the question about how exhausting the control was, 3FOL performed significantly worse compared to other third-person perspectives. Hence, even though it is widely used in non-VR games, we do not see any notable advantages of 3FOL in a VR setup.

5) Design Implications: The outcomes of our experiment allow the formulation of design considerations for further research. In first place, we argue that a 1:1 full-body mapping is not a key requirement for IVBO, as half-body approaches often achieved similarly high scores. This observation is especially important for the design of animals with significantly different skeletons that cannot be mapped to our human anthropology, as we can still induce the IVBO effect under such conditions.

Fig. 6. A difference of 3NAV (left) to 3CAM and 3FOL (right) occurs when subjects walk backwards: the avatar is suddenly facing and "chasing" them.

In general, we note that half-body approaches that map one of our legs to multiple animal limbs should be considered instead of forcing users in a non-upright position such as crouching. Half-body maximizes the IVBO effect compared to less direct mapping modes, yet removes the discomfort induced by full-body controls. However, using our legs only limits the interaction precision, and we recommend mapping fine-grained manipulation tasks to our hands. For instance, we could map the two front limbs of the spider to our arms, which allows users to execute precise actions such as holding objects.

Another observation is related to the choice of perspective. Although third-person approaches were inferior to first-person modes regarding IVBO, we argue that third-person offers a viable option for rapid prototyping of VR animal applications. First-person modes presume a precise motion mapping to perform well, which usually requires tuned IK solutions and knowledge of animal kinesiology. In contrast, third-person controls—probably due to the weaker IVBO—can rely on simple, predefined avatar animations: in our experiment, participants have not noticed any difference nor reported any resentment related to the unsynchronized movements.

V. Conclusion and Future Work

Backed by our supplementary studies, we underpinned the large potential of animal avatars for VR research and applications, be it for education or entertainment. To provide a starting point for future research, we proposed a number of different control modes for upright/flying species, four-legged mammals, and arthropods. Our evaluation revealed that IVBO can be considered for nonhumanoid avatars and led us to a first set of design implications in that area.

We conclude that half-body tracking is a viable alternative to control animals that are not in an upright position as it offers a promising trade-off between fatigue and IVBO. For that reason, we suggest examining such half-body approaches in more depth. To provide higher degrees of control, a combination with sensory substitution [21] might be a viable approach for future research. Finally, as desired by the majority of participants, we propose to enhance the avatars with appropriate capabilities such as flying and see how this would impact IVBO. Hereby, the ultimate goal is the construction of a zoological IVBO framework that would support researchers and practitioners in designing meaningful virtual animals.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put...": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	**Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games** *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games

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Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games

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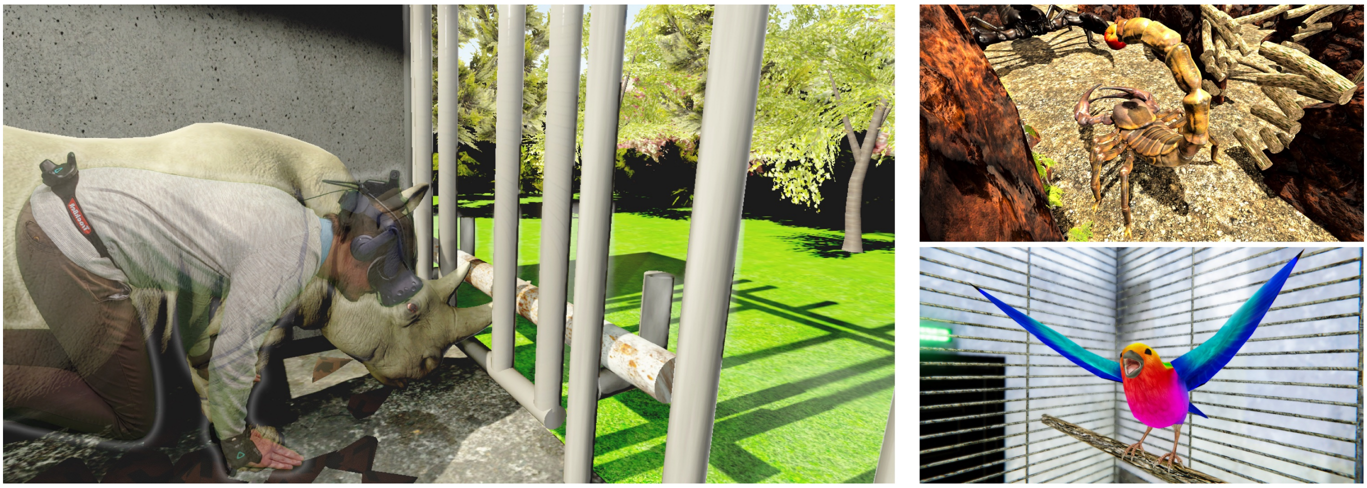

Figure 1. We explore the potential of nonhuman avatars in VR games. The evaluation of our three escape room games for different animal types reveals that players enjoy the control over additional body parts, as such morphologies allow novel, refreshing interactions and enable superhuman abilities.

ABSTRACT

Virtual reality setups are particularly suited to create a tight bond between players and their avatars up to a degree where we start perceiving the virtual representation as our own body. We hypothesize that such an illusion of virtual body ownership (IVBO) has a particularly high, yet overlooked potential for nonhumanoid avatars. To validate our claim, we use the example of three very different creatures—a scorpion, a rhino, and a bird—to explore possible avatar controls and game mechanics based on specific animal abilities. A quantitative evaluation underpins the high game enjoyment arising from embodying such nonhuman morphologies, including additional body parts and obtaining respective superhuman skills, which allows us to derive a set of novel design implications. Furthermore, the experiment reveals a correlation between IVBO and game enjoyment, which is a further indication that nonhumanoid creatures offer a meaningful design space for VR games worth further investigation.

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CCS Concepts

•Human-centered computing → Virtual reality; •Software and its engineering → Interactive games; Virtual worlds software;

Author Keywords

Animal avatars; virtual creatures; animal embodiment; IVBO; virtual reality games; avatar control.

INTRODUCTION

The choice of our virtual representation, our avatar, has a strong influence on how we perceive a game. Hence, introducing novel avatar kinds, beyond stereotypes such as knights and wizards, is a viable option to create refreshing and engaging player experiences. This choice applies even more for virtual reality (VR) games, because such immersive setups are capable of amplifying the bond with our virtual self. That bond can be strong enough such that we start perceiving the virtual representation as our own body—a phenomenon also known as the *illusion of virtual body ownership (IVBO)* [61].

By a smart choice of avatars, VR games could allow us to collect impressions and experiences that would not be possible or would be far less engaging in a nonimmersive setup. One prominent example is games focused on nonhumanoid creatures, be it real animals or mythical creatures. Even though players enjoy "beastly" non-VR games, such as *Black & White* [32] and *Deadly Creatures* [44], similar scenarios are offered very rarely. Especially in VR, where presence and the IVBO effect could significantly intensify our experience when using animal abilities, games like *Eagle Flight* [68] remain an exception.

We see manifold reasons why that potential remains unfulfilled, including the very few studies on creature embodiment in VR, which makes it difficult for game designers to predict whether and how players will perceive animal avatars. Furthermore, as only a few games have touched upon this topic, best practices and design guidelines for such avatars are lacking. In other words, we need further research to understand the challenges and opportunities induced by the nonhuman morphology, e.g., additional limbs and their influence on IVBO, differing postures, and possible control approaches.

Our paper makes two contributions. First, we explore nonhumanoid avatars in VR using escape room games built around three very different animals: a rhino, a scorpion, and a bird (cf. Figure 1). Each game explores a different control mechanism and focuses on distinct "superhuman" skills that are typical for these animals. Our evaluation underpins the resulting high player enjoyment, especially from these animal abilities and additional body parts, such as horns, tails, or wings. Accordingly, we draw design implications for animal avatars and present our lessons learned during the design of such VR games.

Our second contribution is the investigation of IVBO in such scenarios. We study how the nonhuman morphology influences our ability to embody such avatars in VR games. In particular, our evaluation reveals correlations between IVBO, game enjoyment, and presence, and confirms that additional body parts and skills are not an obstacle for inducing IVBO. Hence, we assume that our work will motivate researchers and practitioners to reconsider IVBO-enabled nonhumanoid avatars as an important component of player experience in VR.

RELATED WORK

As our research targets virtual environments, we begin with a brief introduction of the related VR terms before focusing on the embodiment of nonhumanoid avatars. Nowadays, VR has regained attention mostly because of affordable mainstream HMDs, such as HTC Vive [11], which allow players to experience games from a novel perspective. Thereby, researchers [5, 56] usually refer to *immersion* [9] as the technical quality of VR equipment and apply the term *presence* [62, 58] to describe the impact of such devices on our perception. In our case, we are particularly interested in presence, which can be measured as proposed by, e.g., IJsselsteijn et al. [17] and Lombard and Ditton [34].

Immersive technologies not only allow us to experience such a "feeling of being there" [16], but also increase our ability to emphasize our virtual self-representation. We can embody our avatar to a remarkable degree, which is also referred to as the *illusion of virtual body ownership (IVBO)* [35], agency, or body transfer illusion.

IVBO originates in the effect of body ownership. The initial experiments by Botvinick and Cohen [7] introduced the rubber hand illusion: the participant's arm was hidden and replaced by an artificial rubber limb, and stroking both the real and virtual arms created the illusion of actually owning that artificial limb. After further investigations [67], researchers proposed a number of models [66, 13, 43, 30] to explain such an interplay between external stimuli and our internal body perception.

Slater et al. [59] and Banakou et al. [3] transferred the original body ownership effect, including the underlying visuotactile stimulation, to virtual environments. However, in their later work, Slater et al. [61] and Sanchez-Vives et al. [53] revisited the stimuli correlations and concluded that sensorimotor cues are more important than the visuotactile cues, which is an important insight, as VR setups seldom include tactile stimulations. To complete the picture, apart from visuotactile and sensorimotor cues, the IVBO effect is mainly impacted by visuoproprioceptive cues (perspective, body continuity, posture and alignment, appearance, and realism) [60, 61, 42, 37].

IVBO was mainly explored with anthropomorphic characters and realistic representations [35, 31, 18]. For instance, related to the question of avatar customization in games, Waltemate et al. [69] showed that customizable representations lead to significantly higher IVBO effects.

A strong IVBO can produce various changes in player behavior [20, 38], resembling the Proteus Effect by Yee et al. [76]. For instance, the work by Peck et al. [41] revealed a significant reduction in racial bias when players embody a black character. Similarly, virtual race can also affect the drumming style [22]. Other reactions are childish feelings arising from embodying child bodies [3] and an increase in perceived stability when having a robotic avatar [36]. Hence, prior work indicates that IVBO can be used to evoke specific feelings and attributes [25]. We suggest that a strong bond to the creature caused by IVBO can also increase our involvement with environmental issues [1, 4] and our empathy for animals, which, in turn, is transferable to human-human empathy, as shown by Taylor et al. [64].

Researchers have also expressed interest in studying IVBO beyond human morphology. For instance, Riva et al. [48] posed the following question: *But what if, instead of simply extending our morphology, a person could become something else- a bat perhaps or an animal so far removed from the human that it does not even have the same kind of skeleton—an invertebrate, like a lobster?* Interestingly, embodying a bat is even being discussed in philosophy [39]. If we consider exotic body compositions, as in the case of a lobster, that have few properties in common with our human body, the idea of sensory substitution [2] might play an important role. One might also consider such substitution mechanisms as playful interactions: e.g., the echolocation feature of a bat could be replaced by tactile feedback in a VR game.

Given the extreme diversity of real and fictional creatures, it is difficult or even impossible to research IVBO for virtual animals as a whole. Instead, previous research tackled isolated modifications of body parts. For instance, Kilteni et al. [24] were able to stretch the virtual arm up to four times its original length without losing IVBO. Normand et al. [40] used IVBO to induce the feeling of owning a larger belly than in reality. As a first step toward generalization, Blom et al. [6] concluded that strong spatial coincidence of real and virtual body part is not mandatory to produce IVBO.

Certain animals, such as scorpions or rhinos in our study, have additional body parts that players might want to control. In this respect, prior work [14, 15] confirmed that having an additional arm preserves IVBO and induces a double-touch feeling. Steptoe et al. [63] reported effects of IVBO upon attaching a virtual tail-like body extension to the user's virtual character. Clearly, these findings are relevant for a plethora of real and fictive nonhumanoids, such as dragons. The authors also discovered higher degrees of IVBO when the tail movement is synchronized with the real body.

To remain briefly with the example of a dragon as an avatar: Egeberg et al. [12] proposed different ways wing control could be coupled with sensory feedback, and Sikström et al. [57] assessed the influence of sound on IVBO in such scenarios. Won et al. [74] further analyzed our ability to inhabit nonhumanoid avatars that have additional body parts.

Closely related to our research, the works-in-progress paper by Krekhov et al. [27] also suggested embodying virtual animals in VR games. In their preliminary, explorative study, the authors implemented different control approaches for virtual tigers, bats, and spiders, and reported tendencies that IVBO remains intact for such avatars. We continue that work by building on the lessons learned regarding full-body and half-body control approaches, yet focus on embedding this knowledge into games research.

Naturally, we need a way to measure and compare IVBO strength in order to investigate whether and how IVBO influences player experience. In this regard, we point readers to the recent work by Roth et al. [49] that introduced the *alpha IVBO questionnaire* based on a fake mirror scenario study. The authors suggested acceptance, control, and change as the three factors that determine IVBO. As the study by Krekhov et al. [27] relied on this questionnaire to study animal embodiment in VR, we applied the same process to generate comparable results.

A body of literature related to the control of animal avatars should be mentioned in this context. Leite et al. [29] experimented with virtual silhouettes of animals that were used like shadow puppets and controlled by body motion. For 3D cases, Rhodin et al. [45] applied sparse correspondence methods to create a mapping between player movements and animal behavior and tested their approach with species such as spiders and horses. As a next step, Rhodin at al. [46] experimented with the generalization of wave gestures to create control possibilities for, e.g., caterpillar crawling movements. Our research extends these methods by presenting additional mechanisms tailored to animal avatar control.

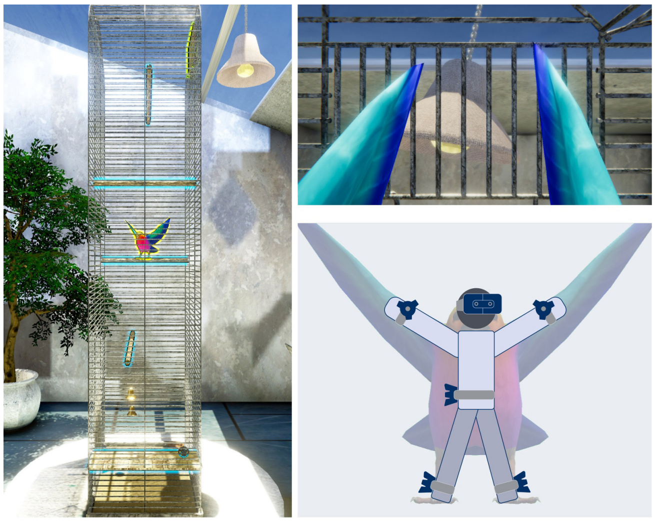

Figure 2. ***Bird Cage.*** **Players embodied a bird that was caught in a cage and had to escape through the top right door (marked yellow). The blue marked rods could be used for rests between the exhausting flights performed by full-body controls (bottom right). Finally, wind gusts had to be created to turn a lamp into a wrecking ball (top right).**

THE VIRTUAL ANIMAL EXPERIENCE

Our main goal is to understand the benefits and limitations of animal avatars in VR games. Unfortunately, prior work indicates that we cannot overgeneralize such research, because animals vary greatly among themselves, be it regarding their skeletons, or postures, or motion. Hence, we focus on a sound methodology for a few sufficiently distinct representatives and provide in-depth insights how such avatars can be embedded in a gaming context. In particular, this section describes our reasoning regarding the choice of animals and their controls, as well as a quantitative evaluation of the outcomes.

Choosing Virtual Animals

One of the main questions to be asked when designing a game with nonhumanoid avatars is which creature to pick. Obviously, this choice is determined by various game design aspects that are not specific to animal avatars. However, the inclusion of such creatures adds degrees of freedom that need to be considered. We focus on two main aspects: the increased interaction design space and the induced challenges in controlling such avatars.

In the first place, playing an animal allows us to naturally inhibit the respective superhuman skills, such as flying as a bird or exploring underwater scenes as a dolphin. We postulate that such natural interactions could be intuitive and easy to learn when done right. Furthermore, the IVBO effect can intensify [3, 36] our perception of such actions due to the increased bond to our avatar compared to non-VR games.

These additional skills are often bound to additional body parts of nonhumanoid creatures. Fortunately, prior work [74] indicates that such additions do not necessarily destroy the IVBO

Figure 3. ***Rhino Room.*** **Players had to mimic the rhino posture (left) and escape from a burning zoo. The blue marked water tap (middle) had to be removed from the wall (right) to extinguish the fire. To open the yellow marked door, players had to use the horn and remove a lock bar (cf. Figure 1).**

effect and can still be intuitively controlled by players [12]. In this respect, we recommend designing the avatar such that the altered morphology is perceived as an extension to our body, instead of being a restriction. For instance, Krekhov et al. [27] reported that players liked the large wings of a bat because they felt like arm extensions and helpful tools, but disliked tiger paws that felt shorter than their actual limbs.

A second important aspect to be considered when designing such games is how the creature should be controlled by the player. To embody animal avatars, it is reasonable to synchronize the movements of the players as precisely as possible with their virtual representation [53]. However, typical room-scale VR equipment tracks only the players' heads and hands. We see three approaches to overcome that barrier: relying on only three tracked positions, including markerless tracking [75], or requiring tracking extensions, such as the HTC Vive Trackers [11].

Even when full-body tracking is available, the question still remains how animals with significantly different postures should be controlled. A prominent example is creatures with non-upright postures, such as typical mammals. A straightforward way would be to crawl on all fours as a player to achieve the most realistic mapping. However, this might cause exhaustion over a longer period of time. As a remedy, *half-body controls* [27] can be applied to remain in an upright posture without noticeable sacrifice of IVBO. Half-body mapping approaches have either no direct mapping between players' legs and the limbs of an animal at all, or one leg is mapped to multiple limbs, which allows us to control creatures like spiders. Apart from fatigue, such controls are beneficial for cases where full-body tracking is not available.

To summarize, finding an optimal virtual creature is a multifaceted process, and we suggest the impact of additional body parts and resulting superhuman skills, as well as possible control approaches be considered during the decision-making. To illustrate that process in more detail, we will showcase a possible selection approach of avatars and game mechanics in the next section.

Example Realization

To study animal avatars in a game context, we created a diverse testbed that supports multiple creatures with Unity 3D [65]. The main idea is based on so-called *escape rooms* [70]: players are placed in a room filled with challenges that have to be solved in order to win/escape. We picked that setting for two particular reasons. First, if virtual and real rooms match in size and shape, locomotion can be achieved by natural walking, which has a positive impact on presence [50, 26] and removes the need for additional, artificial navigation techniques, such as teleportation. Hence, players can focus more on the actual animal experience and are less distracted by accompanying functionalities. Second, escape room games are similar in their concept, which allows us to implement multiple, yet comparable scenarios, i.e., different rooms with different animal avatars. Each room contained two to three quests that involve navigation and object manipulation. In contrast to common escape games, we did not impose any time limitation to remove competition as a factor from our studies.

After picking the overarching game type, we focused on the design of the underlying game mechanics. We set ourselves the objective of building the individual room quests around distinct animal abilities. We selected three animals based their superhuman skills and/or additional body parts: a rhino, a scorpion, and a bird. In particular, our selection included morphologies with different degrees of similarity compared to our human body. A bird has a straightforward mapping, i.e., our arms become wings, and our legs become bird's feet. The horn of the rhino has no direct counterpart and requires a head-oriented interaction that is exotic for human beings. Finally, the scorpion comes with additional limbs, a tail with a sting, and two claws, which is the most differing morphology with at least two nonhumanoid interactions.

Rhino Room

We chose a rhino mainly because of its horn and the related capabilities. We suggest that such head-centered interactions occur seldom in VR games and could offer a unique player experience. In our case, players should use the horn (and paws) to escape from a burning cage, as shown in Figure 3. In particular, the horn was needed to move crates and clear the area in front of a water tap, to remove the tap from the wall to release a jet of water, and, finally, to lift and remove a lock bar that kept the door closed.

We utilized full-body controls with 1:1 motion mapping, i.e., players had to crawl on all fours during the game. Therefore, we positioned additional trackers at the hip and both ankles and wrists, i.e., no Vive controllers were used. We relied on inverse kinematics (IK) [8] to reconstruct the player posture.

Figure 4. ***Scorpion Room.*** **Players remained in an upright posture (left) and used the controllers to open and close the claws and initiate a tail strike. To escape from the labyrinth, players had to cut away several branches (right). The exit-blocking emperor scorpion (middle) had to be pelted with poisoned fruits. The avatar tail was used to pick up these fruits. Aiming during the throwing process was done via a proper hip orientation.**

In particular, we applied a combination of closed-form and iterative solvers to provide the required degrees of freedom yet minimize jittering caused by unavoidable tracking errors. The horn was always visible to the players and placed slightly below the camera, as can be seen in Figure 3.

Scorpion Room

A scorpion offers even more unique interactions compared with a rhino if we allow players to control its tail and claws. In our scenario, depicted in in Figure 4, players had to use these techniques to cut their way through a labyrinth and defeat a giant enemy by throwing a poisoned fruit at it (cf. Figure 1). The fruit had to be picked up and thrown via the sting at the end of the scorpion tail.

To explore a variety of control approaches, we relied on half-body tracking, i.e., an upright posture, instead of 1:1 mapping, as done in the rhino game. We used the tracking data from the HMD, two Vive controllers, and an additional tracker at the hip position. Player arm movement was transferred to the virtual claws via IK. Trigger buttons could be used to open and close the claws to perform cutting. The circular track pad button initiated a tail strike, whereas aiming was performed by hip alignment. We did not track players' legs. Hence, the limbs of the scorpion were equipped with predefined "walking" animations matching the speed of player movement.

Bird Cage

To complete the diverse set of our virtual animals, we also included a flying creature, as can be seen in Figure 2. Being a bird, players could use their virtual wings for two purposes: flying and creating gusts of wind to move objects. To escape from their virtual cage, players had to gain altitude, reach the highest point, and flutter with their wings in sync with the movement of a ceiling lamp, which then gained momentum and broke the cage door. Gaining altitude required significant effort, and players had to rest on rods between their flights.

We used the same tracking setup as in the rhino game, i.e., trackers at hip, wrists, and ankles. Players remained in an upright posture, and their arms were mapped to the wings, i.e., flapping was achieved via rapid up and down arm movements. To create gusts, players moved their arms horizontally instead. Flying around in the cage consisted of two components: flapping to gain altitude, and walking to perform a horizontal transition. We explicitly enforced that horizontal physical movement to minimize cybersickness [28] by reducing the cognitive mismatch between physical and visual feedback. If players stopped waving their arms mid-air, a "falling" procedure was applied. That transition was performed rapidly to prevent cybersickness [26].

EVALUATION

Research Questions and Hypotheses

The main purpose of our study was to investigate how players experience the animal avatars in our three game scenarios to draw conclusions about which aspects of representation, control, and interaction are perceived positively or negatively. Accordingly, our main research questions are:

1: Do animal avatars induce positive player experiences?

2: How do players evaluate the different design decisions regarding posture, visible body parts, and control mapping in our three games?

We assume that slipping into the role of an animal is a novel and interesting experience, and that the control of non-humanoid body parts and the use of related special abilities can raise players' enjoyment and engagement. Our three different realizations allow us to investigate whether a realistic posture and locomotion technique (e.g., crawling), the visibility of certain body parts, and the type of control mapping contribute to or interfere with a positive experience.

Besides the general acceptance of animal avatars and the evaluation of the respective player experiences, we also consider the concept of IVBO. Based on prior findings indicating that IVBO is not limited to human-like bodies [74, 27], we hypothesize that our virtual animal bodies are capable of inducing IVBO as well, and that higher IVBO can be associated with higher perceived presence and game enjoyment. Hence, we want to test the following hypothesis:

H1: IVBO is positively correlated with game enjoyment and perceived presence.

Study Procedure and Applied Measures

We applied a within-subjects design with the game scenario as the independent variable with three levels (rhino, scorpion, bird). After being informed about the study procedure and signing an informed consent, participants filled in a first questionnaire about their demographic data, gaming habits, and prior experiences with VR headsets. We also administered the Immersive Tendencies Questionnaire (ITQ) [72] to check participants' individual tendencies to get immersed in an activity or fiction.

We then introduced the participants to the first game scenario. The three games were played in varying order to avoid biases due to sequence effects. In particular, we counterbalanced the sequence of the three game scenarios across subjects. All sessions followed the same procedure. First, the examiner explained the goal and controls of the game and applied the VR headset, an HTC Vive Pro [10] with a wireless adapter, and HTC Vive Trackers [11]. Subsequently, a neutral mirror scene was started, in which participants saw their animal body avatar and were able to get used to the controls by observing their movements in a big mirror, as can be seen in Figure 5. This scene was displayed for 2 minutes to enable embodiment. The duration is a common choice for IVBO studies, and prior work indicates that even 15 seconds are enough to cause that effect [33]. After the mirror scene, we asked the participants to remove the HMD and administered the acceptance and control subscales of the alpha IVBO questionnaire [49]. We were mainly interested in the IVBO experience while playing and not in the subsequent effects on players' bodily perception, so the change dimension of the IVBO questionnaire was not applied. We decided against performing threat tests for capturing IVBO, because we expected significant sequence effects. Note there is no unified procedure for measuring IVBO, and a threat test is not the only possibility [23, 49]. We decided to use the alpha IVBO questionnaire and checked its reliability by calculating Cronbach's alpha for both subscales (all alphas > 0.82).

Upon completion, we re-equipped the participants with the HMD and launched the main game. Each gaming session lasted about 7 to 10 minutes, depending on how quickly players were able to solve all riddles. After each session, we asked the participants to fill in a questionnaire asking about their experiences during play. We administered the enjoyment subscale of the Intrinsic Motivation Inventory (IMI) [51] to assess general game enjoyment, as well as the Player Experience of Need Satisfaction (PENS) questionnaire [52, 47, 19] to test experienced autonomy, competence, and intuitiveness of controls. We measured the feelings of presence by the Presence Questionnaire [73, 71] and the Igroup Presence Questionnaire (IPQ) [55, 54]. To test for negative physiological effects of using the immersive HMD, we also administered the Simulator Sickness Questionnaire (SSQ) [21]. Finally, we posed some custom, game-specific questions to assess how players evaluated the controls, the required posture during play, as well as the visibility of certain body parts. We also asked whether participants could imagine using this kind of avatar control in other VR games. All administered questionnaire items had to be rated on a unipolar scale ranging from 0 to 6 ("completely disagree" to "completely agree"), except from the SSQ, which had to be rated on a unipolar 4-point scale.

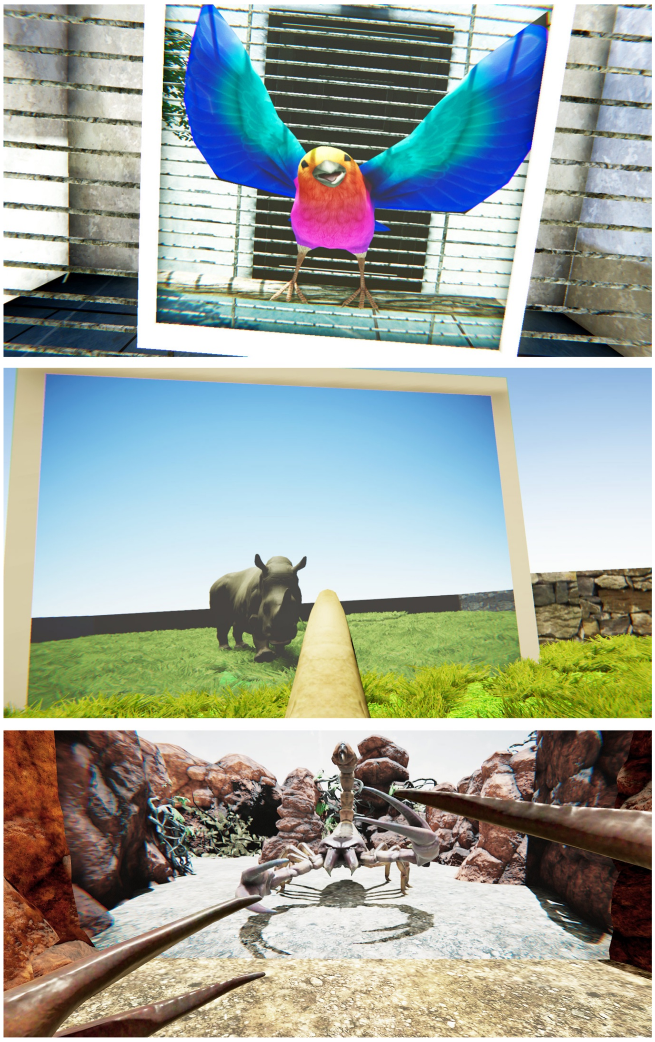

Figure 5. Before each game, players were asked to act in front of a wall-sized mirror for about two minutes to get familiar with their virtual representation and to answer the alpha IVBO questionnaire [49].

Results

In total, 32 persons (19 female, 13 male) with a mean age of 23.7 years (SD = 5.18) participated in our study. Due to recruiting at a university, most of them were students (N = 25), whereas the others were employees. Many participants reported prior experiences with VR headsets (N = 22), but only two of them used VR systems on a regular basis. All participants were familiar with digital games and the majority (N = 24) reported playing digital games regularly.

Players' Experiences with the Three Animal Avatars

Following our research questions, we analyzed participants' ratings of the different animal avatars and their experiences in the three game scenarios. Mean values of all applied questionnaires can be found in Table 1. Considering the scales' range from 0 to 6, almost all aspects were rated above average, indicating a positive experience in all three game scenarios. In particular, IMI scores and perceived presence as measured by the PQ show that players enjoyed the games and felt as if they were actually being and acting in the virtual world. Scores

		Rhino	Scorpion	Bird			
		M (*SD*)	*M* (*SD*)	*M* (*SD*)	*F*	χ^2	*p*
IMI	Enjoyment/Interest	4.46 (0.96)	4.17 (1.37)	4.08 (1.36)	-	0.065	.968
PENS	Competence	3.66 (1.85)	3.03 (1.85)	3.33 (1.66)	-	3.000	.223
	Autonomy	3.82 (1.51)	3.27 (1.53)	3.14 (1.62)	3.562	-	.034 *
	Intuitive controls	5.14 (1.15)	4.50 (1.74)	4.53 (1.35)	-	11.608	.003 *
PQ	Realism	4.09 (1.15)	3.93 (1.19)	3.92 (1.09)	0.493	-	.613
	Possibility to act	4.55 (0.83)	3.98 (0.99)	3.85 (1.06)	7.607	-	.001 *
	Quality of interface	4.91 (1.02)	4.54 (1.21)	4.97 (1.02)	4.142	-	.020 *
	Possibility to examine	4.44 (1.05)	3.89 (1.29)	3.72 (1.24)	-	22.709	< .001 *
	Self-evaluation of performance	4.53 (1.51)	4.19 (1.44)	4.34 (1.24)	-	4.019	.134
	Total	4.42 (0.92)	4.06 (1.02)	4.09 (0.91)	4.162	-	.020 *
IPQ	General	3.88 (1.52)	3.56 (1.68)	3.63 (1.70)	-	2.092	.351
	Spatial presence	4.22 (1.19)	4.07 (1.24)	3.94 (0.99)	1.339	-	.270
	Involvement	3.34 (1.28)	3.02 (1.21)	2.96 (1.26)	2.373	-	.102
IVBO	Acceptance	3.34 (1.15)	3.26 (1.29)	3.46 (1.31)	0.502	-	.608
	Control	4.64 (1.42)	4.40 (1.53)	4.88 (1.26)	-	3.576	.167
SSQ	Nausea	0.21 (0.32)	0.27 (0.38)	0.26 (0.40)	-	2.590	.274
	Oculomotor	0.24 (0.27)	0.35 (0.45)	0.26 (0.34)	-	9.968	.007 *
	Disorientation	0.11 (0.18)	0.19 (0.41)	0.17 (0.42)	-	3.405	.182

* significant main effect at a significance level of $\alpha = .05$

Table 1. Mean scores and standard deviations of the IMI, PENS, PQ, IPQ, IVBO, and SSQ subscales for the three game scenarios (all scales range from 0 to 6, except from SSQ, which ranges from 0 to 3). Significant differences of mean values between conditions were tested by calculating repeated measures ANOVA (*F*) or Friedman tests (χ^2), if data was not normally distributed.

of all three subscales of the SSQ—nausea, oculomotor, and disorientation—were very low in all conditions (all $M < 0.36$), and thus cybersickness was not an issue and can be excluded as a potential confounding variable.

We compared players' experiences in the three game scenarios in terms of the subscales of IMI, PENS, PQ, IPQ, and IVBO to investigate whether the different avatars and interactions were perceived differently. Our analysis of covariance indicated no significant influence of immersive tendencies (ITQ) on our dependent variables, hence we did not further elaborate on that. In advance, we performed Kolmogorov-Smirnov tests to assess all scales for normal distribution as a requirement for parametric calculations. If violated, results of Friedman tests are reported instead of repeated measures ANOVA for comparing the three game scenarios. Bonferroni correction was applied for all post-hoc tests. The main test statistics can be found in Table 1.

Regarding players' need satisfaction (PENS), we found significant differences between the three game scenarios in terms of autonomy and intuitive controls. Post-hoc tests indicate that perceived autonomy was significantly higher when playing with the rhino compared to the scorpion scenario ($p = .049$). The intuitiveness of controls was rated significantly higher in the rhino scenario than in both the scorpion ($p = .012$) and the bird condition ($p = .004$).

Comparisons of the PQ subscales show further significant differences. According to post-hoc tests, participants reported significantly better experiences regarding the possibility to act and the possibility to examine in the rhino scenario than in the other two games (all $p < .004$). Moreover, the total score for presence was significantly higher for the rhino than for the scorpion ($p = .017$). The interface quality, in contrast, was rated significantly lower in the scorpion game compared to the bird scenario ($p = .049$). All other measures did not differ significantly, i.e., we did not find significant differences regarding general game enjoyment or IVBO.

Insights About the Different Postures

As our different scenarios required different postures, we asked how the actual gaming posture was perceived and if participants would have preferred another posture. For the bird and scorpion avatars, participants agreed that the upright posture was comfortable (bird: $M = 4.50$, $SD = 1.48$; scorpion: $M = 5.03$, $SD = 1.26$), whereas the kneeling posture in the rhino condition was rated ambiguously and perceived as being physically demanding by several participants ($M = 3.44$, $SD = 1.98$). However, when asked whether they would prefer an upright playing posture to control the rhino, the majority of players tended to disagree ($M = 2.56$, $SD = 2.41$). In contrast, they agreed that the kneeling posture contributed to the realism of the game ($M = 4.16$, $SD = 1.99$).

	IMI	PQ						IPQ		
	enjoyment	realism	possibility to act	interface quality	possibility to examine	performance	total	general	spatial presence	involvement
	r_s (p)	r_s (p)	r_s (p)	r_s (p)	r_s (p)	r_s (p)	r_s (p)	r_s (p)	r_s (p)	r_s (p)
IVBO - Rhino										
Acceptance	0.068 (.710)	0.511* (.003)	0.312* (.049)	0.480* (.005)	0.404* (.022)	0.329 (.066)	0.508* (.003)	0.192 (0.291)	0.354* (.047)	0.046 (.805)
Control	0.442* (.011)	0.734* (<.001)	0.557* (.001)	0.689* (<.001)	0.612* (<.001)	0.467* (.007)	0.760* (<.001)	0.559* (.001)	0.590* (<.001)	0.022 (.903)
IVBO - Scorpion										
Acceptance	0.357* (.045)	0.428* (.015)	0.438* (.012)	0.272 (.132)	0.461* (.008)	0.399* (.024)	0.460* (.008)	0.560* (.001)	0.496* (.004)	0.349 (.051)
Control	0.572* (.001)	0.742* (<.001)	0.563* (.001)	0.562* (.001)	0.642* (<.001)	0.586* (<.001)	0.769* (<.001)	0.460* (.008)	0.504* (.003)	0.190 (0.297)
IVBO - Bird										
Acceptance	0.397* (.024)	0.481* (.005)	0.585* (<.001)	0.451* (.010)	0.557* (.001)	0.391* (.027)	0.618* (<.001)	0.436* (.013)	0.480* (.005)	0.237 (.192)
Control	0.387* (.029)	0.358* (.044)	0.412* (.019)	0.591* (<.001)	0.478* (.006)	0.324 (.071)	0.501* (.004)	0.474* (.006)	0.520* (.002)	0.163 (.374)

* significant correlation at a significance level of $\alpha = .05$

Table 2. Spearman's rank-order correlation coefficients r_s and p-values that indicate correlations among the IVBO subscales and IMI, PQ, and IPQ.

The bird posture and the mechanics of locomotion (flapping with the arms to move up combined with walking to move horizontally) was also perceived as being realistic (M = 4.84, SD = 1.08). Accordingly, participants did not wish for another posture (M = 1.09, SD = 1.65).

Similar ratings were given for the scorpion: participants rated the posture as being realistic (M = 4.13, SD = 1.95) and did not wish for another posture such as kneeling (M = 1.78, SD = 2.01), although a kneeling posture would be objectively more realistic. When asked whether they had the feeling of being stuck in the ground (due to the low head position), participants were rather inconclusive (M = 3.25, SD = 2.17). During the experiment, we observed that some participants were indeed a bit irritated at the beginning, but got used to the mismatch between their own and the avatar's body size quite quickly.

Controls

Overall, the high ratings for PENS' intuitive controls confirm that participants had no problems moving and interacting in the game world and using the animals' abilities in all three scenarios. Although our three animal avatars are rather different in terms of posture and control mapping, participants stated in all three cases that they could very well imagine using this kind of avatar control in other VR games (rhino: M = 4.56, SD = 1.78; scorpion: M = 4.94, SD = 1.44; bird: M = 4.75, SD = 1.55).

Visibility of Body Parts

Regarding the visibility of certain body parts, we were interested in players' opinions about the usefulness of such visualizations and the possible interferences. In the rhino game, the horn was displayed in the players' sight throughout the game. However, the horn was neither perceived as being disruptive (M = 0.69, SD = 1.18) nor resulted in the perception of a constrained field of view (M = 0.97, SD = 1.26). In contrast, participants enjoyed using the horn as a tool (M = 4.78, SD = 1.60).

In the bird cage scenario, apart from the wings, the bird's feet were also displayed. Participants appreciated this display, because they rated this feature as being helpful for landing on the rods (M = 5.22, SD = 1.49).

Special Abilities

We also asked players about their opinions regarding the special abilities they could use as animals. Participants agreed that the use of the horn of the rhino enriched the whole experience (M = 4.91, SD = 1.33). The scorpion's sting was rated as very interesting (M = 4.44, SD = 1.59), and players also liked to use the claws (M = 3.81, SD = 1.86). Moreover, players rated the experience of flying as a bird as very interesting (M = 5.12, SD = 1.36) as they did the bird's ability to create gusts of wind (M = 4.19, SD = 1.93).

Correlations between IVBO, Enjoyment, and Presence

Mean values of IVBO control are rather high, and mean values of IVBO acceptance are above average, as well, which indicates that players have experienced IVBO while controlling our animal avatars. To test our hypothesis regarding the relation between IVBO and the player experience (H1), we analyzed the correlations between the two subscales of the IVBO questionnaire and the subscales of IMI, PQ, and IPQ. We calculated Spearman's rank correlation coefficients (Spearman's rho) due to a lack of normal distribution of some scales. Table 2 summarizes the results for each game scenario.

Overall, we found significant positive correlations between IVBO and nearly all PQ and IPQ subscales: ratings of experienced realism, the possibility to act, the possibility to examine, PQ total, and spatial presence are consistently significantly correlated with both IVBO dimensions in all three games. Furthermore, IVBO control also significantly correlates with the perceived interface quality and the general feeling of presence as measured by the IPQ. IVBO acceptance correlates with the interface quality except from the scorpion scenario, and with general presence except from the rhino scenario. The only scale not significantly correlated with IVBO in any scenario is IPQ involvement.

Regarding game enjoyment, our analysis shows significant positive correlations between IVBO control and IMI enjoyment scores in all three scenarios. The correlation between IVBO acceptance and enjoyment is significant in the bird cage and the scorpion room, whereas there is no correlation in the rhino condition. In sum, our results mainly support our hypothesis H1.

Discussion and Design Implications

Our results indicate that animal avatars in VR games can induce positive player experiences. We implemented three games with animal avatars that are very different regarding body features and abilities, and in all cases players reported high enjoyment and high presence, i.e., the feeling of actually being in the virtual world and being the rhino, scorpion, or bird. Participants particularly appreciated the novel body experiences and nonhumanoid perspectives, as well as the use of the special animal abilities.

Special abilities

The feedback of participants on our three games shows that players are very interested in performing actions that they are not able to perform in real life. For instance, they were fascinated by the ability to fly upwards using their wings as a bird, and they enjoyed testing how they could manipulate objects with their rhino horn. We reason that such superhuman abilities significantly contribute to players' enjoyment and their motivation to play. Hence, the main game mechanics of games featuring animal avatars should **foster the animal's specific characteristics and abilities** to create novel, fanciful experiences. Designers should take advantage of players' curiosity and expose unique animal features.

Player Posture and Controls

In all three games, the adopted postures were perceived positively and without an explicit desire for alternatives. In other words, there is no indication that a realistic yet uncomfortable posture (rhino) is better or worse than a convenient and upright but unrealistic posture (scorpion). However, the statements regarding crawling on the floor as a rhino were quite ambivalent, i.e., some of the participants enjoyed such an experience, whereas others became rapidly exhausted by that activity. Note that the rhino, however, outperformed other animals in certain subscales, such as autonomy (PENS), intuitive controls (PENS), and the possibility to act (PQ). Hence, a 1:1 mapping where players have to behave exactly like they would expect from their animal avatar is easier to grasp and is perceived as very realistic.

Similarly, our results did not disqualify or favor any particular control approach – all three controls were rated as very intuitive and participants could imagine using such approaches in other VR games. Hence, we suggest **controls be designed based on the game-related animal abilities and the target audience**. For instance, we assume that children are more willing to spend their time crawling on the floor compared to elderly adults. In general, transferring as many player movements as possible onto the avatar is a reasonable approach, especially considering the positive influence on IVBO [53]. However, as we have seen in the scorpion case, less straightforward mappings can be equally engaging and fun without enforcing an uncomfortable posture. Furthermore, such implementations can be achieved with less tracking equipment.

Visible body parts

Game designers have different approaches regarding the visibility of the avatar's body in first-person mode. From our experience, we would not recommend visualizing the whole body, as the avatar head position often leads to confusing viewports when players look down on them. Instead, we suggest **the visualization be limited to body parts that can be directly controlled by the player**, e.g., claws, tails, wings, and horns. In particular, the additional body parts, although reducing the visible area, are not perceived as disturbing. For instance, participants rated the horn as a helpful tool and reported that the bird's feet facilitate the landing on thin rods. Furthermore, seeing animal body parts like claws moving in sync with our own body increases our awareness of embodiment.

Morphology

Considering the morphology of our three animal avatars, our results indicate that players had no problems with controlling bodies that are not similar to the human shape. Even the control of the scorpion, which has several additional limbs, claws, and a tail, was perceived as intuitive and did not cause any confusion. In contrast, we observed that players particularly liked additional body parts such as the scorpion's sting or the horn of the rhino. Hence, we challenge game designers to **consider extraordinary animal shapes** and derive innovative game mechanics. We should not back off from adopting complex body compositions as long as they are associated with interesting possibilities for interaction design. In our three games, we always focused on the outstanding bodily features of the animals and linked them to certain player abilities (e.g., create gusts of wind) to **give significance to them**. We suggest that additional or missing body parts compared to the human body should enrich players' opportunities to examine and interact with the virtual world and not appear as an impairment. This way, we can foster players' experience of having superhuman capabilities.

IVBO

Finally, we conclude that additional body parts or a nonhuman body shape do not inhibit an avatar's potential to induce IVBO. Our three exemplary animal avatars illustrate that IVBO is not limited to body models that are similar to the human body. With regard to our hypothesis H1, our results reveal that IVBO—which was measured prior to the gaming sessions and is, thus, not biased by the subsequent game experience—is positively correlated with game enjoyment and perceived presence. This finding indicates that IVBO may contribute to a positive player experience. Hence, we conclude that **IVBO is a considerable factor when designing nonhumanoid VR avatars**. To foster IVBO in a game, we suggest that game designers provide players with possibilities to see their virtual body (e.g., in mirrors or water reflections) to increase awareness of their virtual representation.

LIMITATIONS OF THE STUDY

Our derived design implications are based especially on the three evaluated scenarios. Hence, we need to consider a set of associated limitations to prevent possible misinterpretation of the findings. In the first place, our main goal was to expose a complete pipeline of embedding animal avatars into VR games. We aimed to raise the awareness regarding the wide variety of decisions (e.g., posture, animal type, mapping/controls, special abilities, morphologies, locomotion) that have to be considered during such a game development process. As a result, our evaluated scenarios are rather complex games with a number of possibly influential variables that might limit the generalizability. For instance, the general appeal of an animal, e.g., a dangerous scorpion vs. a domestic bird, might impact our game enjoyment. Well-known species, such as a rhino, might be more intuitive to control than exotic creatures with abilities unknown to us. And although we removed artificial VR navigation techniques (e.g., teleportation) by matching the size of the virtual environment to the physical room, the different locomotion (flying vs. crouching vs. walking) could still have a considerable impact on the player experience. Finally, although all three scenarios were escape games, the particular quests could have influenced the outcome. In other words, we emphasize that the direct comparison of the three study conditions should be interpreted with these limitations in mind and that the reason behind our variety of scenarios was not the comparison per se, but our strive to cover as much of the animal avatar design space as possible to create a comprehensive starting point for future explorations. Also, comparative studies in the future would benefit from an additional control group with a human avatar for a better assessment of the animals' influence on IVBO and game enjoyment compared to a rather traditional virtual representation.

Another important limitation to be mentioned is that we did not involve animal/domain experts during the design phase and pretests of our study. Our decision making regaring the choice of animal avatars and, even more important, their abilities and interactions, was made without the input of an expert. The latter could have provided additional input regarding the realistic behavior of animals and our perception of such species.

As a next step, we suggest to focus on particular avatar components in a more targeted study to build a theoretical framework that provides an isolated in-depth exploration of major factors, such as locomotion, altered or additional body parts, and appeal. We suggest that such isolated insights should be gathered as a second step after seeing the "whole picture", i.e., how such animals work or do not work in games. For instance, prior work [27] reported that embodying a tiger while crawling on all fours was disliked by the participants, whereas a rhino, being a very similar mammal, provided the highest enjoyment in our scenario. Hence, we suppose that it is not just the familiarity with an animal or the intuitive locomotion, but rather subtle details, e.g., the additional horn, that can significantly alter our experience of such avatars and, thus, need further research.

For further studies, we also recommend expanding the age range of the participants. In our case, most participants were students due to the acquisition at the university, which limits the applicability of our findings. Instead, it is likely that aspects such as the necessary physical effort or the perceived avatar appeal are experienced differently by other age groups. Consequently, the age of the target audience might be an important design consideration and should be explored in future work.

CONCLUSION AND FUTURE WORK

Our work investigated the hidden potential of animal avatars. We focused on virtual reality games because of the related IVBO effect that allows us to embody our avatar and perceive certain player interactions in a more intensive way. Accordingly, our studies supported our general assumption that games created around animal avatars could lead to great enjoyment. In particular, players liked the interactions resulting from additional body parts, such as wings and horns. In this regard, we proposed different ways to control animals with such differing morphologies and discussed related design implications for animal-centered VR games.

As a particular finding, we reported a correlation among IVBO, presence, and game enjoyment. Since our studies had a different emphasis, i.e., the general usefulness of animal avatars, we cannot disentangle these relations in detail. However, we see our results as evidence for the importance of IVBO for VR games in general, be it human or animal avatars. Hence, we propose an in-depth investigation of that overarching topic as possible follow-up research. Ultimately, we assume that a further exploration will encourage researchers and practitioners to consider IVBO as a helpful tool that allows the creation of novel, engaging player experiences that cannot be realized in non-VR games.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put…": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	**"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games** *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

“It’s a Matter of Perspective”: Designing Immersive Character Transitions for VR Games

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“It’s a Matter of Perspective”: Designing Immersive Character Transitions for VR Games

Under Review, Submitted to CHI’23

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Figure 1: We explore the design of immersive transitions between player characters in VR games. After analyzing existing multiprotagonist titles, we present two promising transition concepts. One of the proposed techniques switches to a scaled third-person perspective before transitioning to the next avatar.

ABSTRACT

Storytelling allows us to widen our limited point of view and perceive the world from different perspectives. VR games intensify this storytelling experience by letting players take the role of the main protagonist. However, in contrast to films, novels, or games, VR experiences often remain centered around one single character without using the potential of complex multiprotagonist plots. Our work engages in this critical topic by investigating the design of immersive and natural transitions between different characters. Such techniques form the basis for believable and complex multiprotagonist narratives. After extracting different design approaches from existing VR games, we establish design goals for better character transitions and present two promising design concepts based on our games analysis and prior research. A concluding user study demonstrates the unique strengths and weaknesses of both techniques and reveals future research directions.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; • **Software and its engineering** → *Virtual worlds software*; Interactive games.

KEYWORDS

virtual reality games, game characters, transitions, perspectives, virtual avatars, embodiment

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1 INTRODUCTION

Stories shape our life: they entertain, teach, and illustrate otherwise complicated facts. Above all, storytelling permits us to experience the world from different perspectives and thereby challenge our limited point of view [137]. Despite being younger than most other media types, digital games possess unmatched storytelling capabilities regarding personal meaning and identification. Compared to literature, drama, or films, interactive games allow players to control the protagonist's actions directly. Depending on the game and genre, players decide on their avatar's appearance, character traits, and future decisions, thus reshaping the narrative's further progression [80]. This interactivity enables players to identify and empathize on a much more personal and intense level with the protagonists and their actions [19, 62] and form an emotional attachment [14].

VR games intensify this experience further. Players fully emerge into the immersive game world and take the role of the protagonist, performing the actions on their own. This perspective fosters identification and can also lead to the sensation of virtual body ownership, where players perceive the virtual avatar's body as their own [76, 118]. Past research has shown that these experiences might provoke changes in the users' attitudes, such as reducing racial bias [97] or provoking childish feelings [10]. Such effects further increase the potential impact of interactive and immersive narratives in VR.

However, many stories remain flat and one-sided if perceived from only a single point of view. Thus, it has long been good practice in films, novels, and dramas to employ plots with multiple main protagonists, such as network plots [124] or ensemble films [6]. A good example is the film *Vantage Point* [88], which repeatedly narrates the series of events from eight perspectives. The complete plot unfolds only after experiencing all the different viewpoints. Similar narrative concepts have also found their way into many games that incorporate multiple playable characters and switch at least for single chapters between them.

Narrating the story from different viewpoints fosters perspective-taking among the players. The result is a better and more emotionalized understanding of the protagonists' different motive forces and decisional backgrounds. Games employ multiple-character plots for different purposes and in varying degrees. Some titles, such as *The Witcher 3: Wild Hunt* [18], switch to a different protagonist for a short flashback. Others center their main storyline around a group of playable main characters, each with its own backstory (cf. *Grand Theft Auto V* [103]). The third group of games even switches between protagonists and antagonists, thereby challenging the stereotypical friend-foe paradigm. This last design choice, especially, can provoke intense emotional reactions among players by forcing new perspectives on them [34]. A recent example is the action-adventure game *The Last of Us Part II* [90], which caused controversy for its choice of the story's protagonists [125].

What has become a frequent theme in games has remained an exception for virtual experiences. In the first part of our work, we extracted VR games featuring more than one playable character from the different game stores. Despite evaluating 986 distinct titles, we identified only 18 games fitting our search criteria. The minimal prevalence of multiprotagonist plots is astonishing and reveals an unused potential, considering that the immersive nature of virtual environments could greatly improve the experience of taking different perspectives in storytelling. One of the main challenges impeding a broader application of such complex plots is designing proper transitions between the different playable characters. In comparison to other games, VR players are known to be much more sensitive to interruptions in the game's flow, disorientation through instant relocations, and cybersickness induced by artificial motions.

Considering that there is, to our knowledge, only very little prior work, we introduce the vital topic of immersive character transitions through multiple research steps. Our first contribution is an analysis of VR games featuring multiple protagonists. After searching the major app stores and extracting fitting titles, we categorize the different transition types and designs into multiple categories. The results reveal that most of the games avoid character transitions by either splitting the plot into separate sections that are experienced from a single point of view or by permitting controlling multiple characters simultaneously, e.g., through combining first-person and third-person interactions. Only few games support free or orchestrated transitions between different protagonists in the same scene. Focussing on this third category, our second contribution is a set of design goals for immersive character transitions and the development of two different transition concepts based on the game analysis and prior research. The first technique pauses the game and displays an interface indicating the next character and their position in the world. The second approach switches to a third-person perspective and uses a quick forward translation to transport the players to their next avatar (see Figure 1).

In the last part of our work, we evaluate how both transition concepts compare regarding our introduced design goals: preserving the players' presence, providing necessary transition information, avoiding cybersickness, and fostering embodiment and perspective-taking. The results of our exploratory between-subject study reveal that the participants generally welcome the use of more than one player character in a game. Also, the concept based on perspective-switching boosts spatial orientation, realism, and the acceptance of the virtual avatars compared to displaying a map while pausing the game. From these results, we identify key strengths and weaknesses of both concepts and derive further research directions from the subjects' feedback. We will build upon this grounding research to deepen our understanding of immersive multicharacter plots in future work.

Telling stories from multiple perspectives is not only a promising narration technique that can deepen the players' connection and involvement with the plot. It also encourages players to widen their own point of view and enhance their perspective-taking skills in real life. In times when more and more people encapsulate themselves in a bubble and block opposing views, such narrative contents are more valuable than ever before. With our work, we want to provide a foundation for further research on this novel topic and assist developers in realizing immersive character transitions for future narrative VR games.

2 RELATED WORK

In this section, we cover the research relevant to this paper. Our work belongs to VR games research and draws from various fields, including storytelling, body ownership, and perspective-switching. Therefore, we first introduce the basic concepts of storytelling and narration while focussing primarily on virtual environments and multicharacter plots. Next, we outline the current state of research on game avatars and character identification. As immersive experiences can induce a feeling of owning the virtual body, we also introduce the illusion of virtual body ownership (IVBO). Finally, we briefly cover the use of different perspectives in VR.

2.1 Storytelling and Narration

When talking about storytelling, the term *story* is commonly used to describe the told content [78], whereas the *narrative* relates to the story's events [20]. The term *narration* often describes the actual storytelling process in the broad public. However, there is a clear distinction between narration and drama [78], which dates back to Plato [136] and Aristotle [5]: Narrations tell a story from a fixed point of view that an implicit or explicit narrator determines. In contrast, dramas enact a story and cannot rigidly control the audience's point of view. Following this definition, most interactive narrations should rather be considered interactive dramas [68, 78, 82, 83].

Extending the previous definition to virtual environments, we distinguish three different types of immersive storytelling. Similar to films, cinematic VR does not include interactive elements but uses immersion to increase involvement and appreciation for the plot [17, 95, 129]. Interactive narratives are stories that leave minimal choices to the viewer [78], whereas in interactive dramas, the player participates in the story through dramatic enactment [78, 82, 89]. For the scope of this paper, we focus primarily on interactive games belonging to the last type of immersive storytelling.

2.2 Multiprotagonist Narratives

A common narration technique in films is to switch between multiple main protagonists. In general, switching between points of view allows the audience to experience different perspectives as the events unfold. However, literature often distinguishes between different subcategories of this technique. Multiple protagonists films [6] are characterized by a single plot that focuses on a group of people, of whom multiple protagonists must be of equal importance. Network plots [124] tell the stories of multiple characters whose paths should intercept or affect each other at least once. Finally, ensemble films [6] do not have a main plot but narrate several simultaneous stories of equal importance. Whereas these techniques have not yet found broader adoption in VR storytelling, a recent project designed a single-narrative, multiple-point-of-view experience where users could freely switch between protagonists [78]. Early research on multiprotagonist games revealed that players identify with multiple characters, although not equally with all [112]. A second study [34] analyzed the effects of forced protagonist switches on the player-character relationship. Depending on the type of character, this switch may be perceived critically, for it interrupts the players' agency and forces them to accept a new, potentially contradicting, perspective.

2.3 Characters, Protagonists, and Avatars

Characters form the central part of each story [40], regardless of whether they are heroes or enemies [3, 54]. Apart from the story's main protagonist and antagonist, characters with various functions and traits populate a plot, such as mentors, companions, or competitors [135]. In contrast to the pure spectatorship of passive media, games allow players not only to identify and empathize but also to interact with their own and other characters [80]. In many cases, games clearly differentiate between the controllable player character (PC) and other nonplayer characters (NPCs) [54]. Apart from granting agency through direct control of the avatar, many games also give players customizability of names, appearances, character traits, and story decisions [74].

These actions lead to a much more personal experience and allow players to identify more deeply with the protagonist [19, 62]. In this context, *identification* is commonly defined as the degree to which players imagine being a particular character [23]. Players can identify with both playable characters and NPCs [104] and experience identification for various reasons. The similarity concerning appearance, beliefs, or personalities between players and characters is fundamental for identification [133]. In the case of wishful identification [49], the players' ideals regarding specific traits or qualities influence their relationship with a character. For example, research has demonstrated that players with a high body mass index prefer playing characters with their ideal body shape [133]. However, identification is often only a temporary sensation that may change or vanish as the game progresses [62].

Past research has revealed that identifying with a game character can increase players' autonomy, immersion, empathy, and intrinsic motivation [11, 13, 57, 133]. It is also a predictor of the general play experience [41, 72, 73], the time spent in a game [12], and the experienced enjoyment [47]. Another interesting consequence is the mimesis effect, where players often choose narrative choices that correspond with their role in the game [28]. Apart from identification, players also form emotional bonds with believable characters [54]. Attachment to game characters [11, 57] comes in various forms, ranging from respect for the antagonist to feeling responsible for a protégé. Bopp et al. [14] identify three main types of attachment concerning playable protagonists: excitement for the character's capabilities, admiration for personal role models, and sharing similar experiences. Finally, it has been argued that avatar embodiment in virtual experiences might amplify the sensations of identification and emotional attachment even further as players become their avatars [75].

2.4 Body Ownership

In VR, the players' relation to their character can exceed the identification experienced in other games. Instead, they might develop a sensation of embodying a different avatar from their own. Research on this effect originates in experiments that produced illusory ownership of a fake rubber hand [16, 109]. After this early work, the effect was extended to whole bodies [31, 71], faces [126], and voices [142]. Especially in the case of full-body illusion, research revealed that the own self-location drifts toward the virtual body [9, 53, 70, 71]. This sensation might even influence the experienced singularity of the self and lead to a simultaneous identification with two distinct bodies [9, 70, 71]. Researchers have proposed several models to explain the underlying connections between external stimuli and these cognitive body perceptions [31, 71, 98, 127].

The illusion of owning a different body is also transferrable to virtual environments [10, 113]. Therefore, tracking hardware captures the users' movements, which are used to animate a virtual character. This technical process is called *avatar embodiment* [118] and may lead to the *illusion of virtual body ownership* (IVBO), where users perceive the avatar as their own body [76]. Multiple factors are crucial for evoking this psychological sensation. From the original experiments on the rubber hand illusion, we know that synchronous visuotactile stimulations are effective [128], even though later research found that sensorimotor cues are more powerful [107, 115]. The third category impacting the IVBO effect comprises visuoproprioceptive cues [81], such as body continuity [114], realism [4], customizability [134], or perspectives [115]. Whereas most researchers have used the first-person perspective in their studies, prior work did not find significant differences compared to the third-person perspective when combined with visuomotor synchrony [25]. One major disadvantage of the first-person view is the limited visibility of one's own body, commonly countered by virtual mirrors [67]. Not all of the cues mentioned above must be present to induce IVBO. Instead, a subset can suffice [107]. However, a disruption in just one of these factors might easily break the illusion [63]. Finally, proper transitions from the real world to the virtual environments have also been shown to benefit the experienced IVBO and spatial presence [56].

Prior work has evoked IVBO with various avatars differing in gender [115], age [10], race [97], or body shape [59, 92, 132]. It is also possible to induce body ownership for nonhuman characters [76], avatars with transformed or additional body parts [32, 45, 60, 121, 138], and even for animals [64, 66]. Using virtual bodies offers various benefits to the players' immersion [118], game experience [75], distance estimation [102], and spatial knowledge [30, 69]. Another potent consequence of body ownership is the so-called Proteus effect [140], describing the unconscious projection of avatar characteristics on the players' self-perception. Famous examples include evoking childish feelings [10], increasing the perceived strength when playing tough characters [77], or reducing racial bias when embodying black characters [97].

Despite extensive research on the factors that form the IVBO effect, only very recent work has focused on effectively measuring the body ownership sensation via standardized questionnaires [27]. Gonzalez-Franco and Peck [42] reviewed over 30 questionnaire-based embodiment studies and condensed a general 25-item questionnaire, which was recently refined into a validated 16-item version [96]. At the same time, Roth et al. [106] constructed the preliminary alpha IVBO questionnaire, which ultimately led to the Virtual Embodiment Questionnaire (VEQ) [105]. Whereas the work by Peck and Gonzalez-Franco [96] focuses primarily on the differences between the real and virtual body, the VEQ [105] emphasizes the acceptance and the agency, that is, experiencing the avatar's body and actions as one's owns. Thus, we consider it more suited for our game context. Recently, Eubanks et al. [35] also proposed a short questionnaire to be used in VR, which is missing a thorough validation due to COVID-19.

2.5 Perspectives and Transitions

One of the character transition techniques we present in this paper is based on the *Outstanding* locomotion technique for large virtual environments [21, 22], which uses dynamic perspective switching between the first-person and third-person view. Most VR applications heavily rely on the first-person perspective (1PP), but it cannot be considered superior to the third-person perspective (3PP). Instead, both have unique strengths and weaknesses. According to Gorisse et al. [43], 1PP is best suited for interaction-intensive tasks, whereas 3PP provides superior spatial awareness and environmental perception. Additionally, the Outstanding technique scales the players to giant size. This concept was previously used for locomotion purposes [1, 65]. Scaling the complete player, including the eye distance, prevents cybersickness and produces a miniature world effect [101, 139].

Even though our technique draws from previous locomotion concepts and also displaces the players, it does not grant free navigation but focusses on automatic and predetermined transitions from one character to the next. Similar transition techniques have mainly focussed on moving the users between different scenes [85] or between the virtual environment and the real world [50, 120]. A well-designed transition can maintain spatial perception and continuity [141], whereas abrupt cuts could break the users' presence [93] by drawing attention to the virtuality of the scene [85]. Predictable and less abrupt transitions are favorable in terms of continuity, especially if they grant a preview into the next scene [51].

Another common application area for transitioning between different viewpoints is cinematic VR. A common goal with immersive cinematic content is to align the points of attention [15] and maintain continuity through spatial relations, such as establishing shots, eyeline matches, or the 180° rule [61]. In this context, prior research has emphasized the superiority of animated transformations, as instant relocations could easily disorient and confuse users [61, 86]. However, animated transitions in virtual environments are also likely to induce cybersickness [46, 84]. Therefore, we limit the duration of our animated movements and use the original and evaluated transition curve of the Outstanding concept [22].

3 ANALYZING CHARACTER TRANSITIONS IN PUBLISHED VR GAMES

Despite its potential for immersive storytelling, multi-protagonist plots remain an exception in current VR games. Most developers construct the games' stories around just one playable character. This design choice severely restricts storytelling capabilities and prevents advanced plots that force the audience to experience events from multiple perspectives. Furthermore, prior work on designing immersive character switches is almost nonexistent to our knowledge. However, this lack of research bears additional risks. Poorly designed transitions between characters and places might disorient players, break their flow and presence, and thereby reduce the story's impact. Therefore, we consider immersive character transitions a vital topic worth investigating. Given the novelty of this research area, our first step was to identify published VR games employing more than one playable character. With this step, we wanted to identify commonly used techniques and determine potential issues. Our gathering and analysis process was structured into three consecutive steps: preselecting potentially-matching titles, identifying relevant VR games with multiple playable characters, and structuring the used transition techniques.

3.1 Preselection

We started by defining our search criteria for identifying VR games with multiprotagonist plots. We first excluded customizable avatars since purely cosmetic changes in appearance do not add to the game's plot. Also, we were not interested in the concept of hero classes with different abilities. After choosing the avatar according to the preferred playstyle, players would continue with just one character at their disposal. Finally, we also decided to require at least a minimal story aspect. Whereas sports games or simulations might include the ability to command multiple characters, these cases cannot be considered multiprotagonist plots regarding the definitions in the related work section.

Even though these criteria would exclude most available titles, they do not necessarily apply to complete game genres. Additionally, categorization and filtering of games differs between different VR stores and is partially user-generated. Therefore, we decided to begin our search without predefining search conditions and exclude the nonmatching titles in a manual second step. The only exception was limiting the search to games with at least 200 reviews to avoid considering very early prototypes or proofs of concept that are especially found in the SteamVR store. We used the VRDB webpage [44] to extract matching titles from the Oculus Rift [37], Oculus Quest [36], and SteamVR [131] stores. Filtering for reviews did not apply to the PlayStation VR platform [116], as its store does not support public reviews. In the end, the search resulted in 441 SteamVR games, 202 Oculus Rift games, 220 Oculus Quest games, and 474 PlayStationVR games. Some of these titles are distributed on multiple platforms, which led to a total of 986 distinct VR games.

We then went through all games in the first selection round and considered readily available information, such as titles, descriptions, tags, trailers, and pictures. According to these data, we excluded a majority of games that obviously fell into the categories mentioned above. In particular, we eliminated most sports games, racing, flight, and battle simulators, rhythm games, atmospheric and artistic experiences, noninteractive movies, sandboxes, and arcade games. Puzzle and strategy games and multiplayer shooters without a story were also excluded. After this preselection, only 357 games of the original 986 titles remained.

3.2 Identifying Relevant Titles

After preselection, we reiterated the remaining titles and determined whether they fit our search and contained multiple playable characters. Therefore, we reevaluated the previously mentioned information, namely descriptions, trailers, and screenshots, and considered reviews, gameplay videos, and tests. In some cases, we could also resort to our own experiences. We played parts of the games in doubt to gain a firsthand impression. The vast majority of 327 games could be easily excluded, as they did not feature more than one character. The remaining 30 titles required a more considerate look and multiple discussion sessions. With regards to our search criteria and the definitions of multiprotagonist narratives, we decided to consider only a subset of 18 titles as multicharacter games.

The other 12 games offer interesting concepts but do not fully match our definition. For example, in *The Invisible Hours* [123], players experience a network plot. They can rewind the action and switch between the different protagonists freely. However, the players are just passive bystanders and cannot influence the story's outcome. In *Lone Echo 2* [100], the players take control of a single robot. As the game progresses, the main protagonist possesses different body shells, and surrounding NPCs treat these appearances as different personalities. Despite these alterations, the players consider themselves as only one single character throughout the game. The final selection of the 18 games is depicted in Table 1.

3.3 Structuring Similar Techniques

In the final step, we iterated over the selected games and grouped them into categories sharing similar character transition concepts. Therefore, we determined how the different characters relate to each other and how the transition between them is designed and invoked for each game. Multiple discussion sessions culminated in four groups of games, depending on whether the transition between characters is controlled by the players, orchestrated by the narration, or split into separate chapters. The last group comprises titles supporting the simultaneous control of multiple characters and consists of two subcategories. Games that combine gameplay elements of multiple categories were assigned to the most fitting group.

Group 1: Player-controlled Transitions. In the games of the first category, players can switch between multiple characters at any time. These characters are located in the same environment and often connected through a direct line of sight. In *Eden-Tomorrow* [117], players take control of a human and a drone. Both differ in abilities and locomotion and require the players to switch regularly to solve puzzles. The transition itself is limited to a fast fade and happens almost instantaneously. In *Psychonauts in the Rhombus of Ruin* [29], switching between characters is used as the primary locomotion technique. Players can possess nearby crew members, which triggers a short swirl animation. Afterward, players take the character's place and can interact with the environment. In contrast to the previous games, *Wind Wind* [33] uses a third-person view to display the complete scene. The character transition changes only the players' controls without altering the perspective.

Group 2: Orchestrated Transitions. The second category encompasses games with automatic transitions between protagonists. The game *Araya* [79] tells a story through the eyes of three main characters. Therefore, the narration switches automatically between protagonists and repeats the events from different perspectives. The game uses a minimalistic transition by fading to black and displaying the next character's name. Similarly, in *The Assembly* [91], players experience a double journey of two protagonists, whose

Table 1: The list of 18 VR games featuring multiple playable protagonists that were identified during our game analysis. The titles are categorized into different groups based on the character transition technique.

Game	Characters	Transition
Group 1: Player-controlled Transitions		
Eden-Tomorrow [117]	two characters: human and drone	instant switch on demand
Psychonauts in the Rhombus of Ruin [29]	possess crew members at will and interact as them	blend with swirl and fade effect
Wind Wind [33]	two characters (3PP) in shared level	switch control immediately
Group 2: Orchestrated Transitions		
Araya [79]	network plot (3 protagonists), automatic switch	fade to black and display name
The Assembly [91]	double journey (2 protagonists) with interweaving stories, automatic switches	loading screen, chapter title and next character
DreamWorks Voltron VR Chronicles [26]	single plot (3PP), switch to various characters (1PP) for short sections automatically	short black fade
Group 3: Separated Chapters		
Contagion VR: Outbreak [87]	experience zombie apocalypse through different perspectives	separated in scenarios, accessible via main menu
The Walking Dead Onslaught [122]	NPC tells players stories at a campfire, players experience stories in 1PP	fade to black and display chapter title
Asgard's Wrath [108]	player is a god possessing five main characters. Separated chapters, later stages permit character switching	loading screen: character model and map; at altars players switch to giant 3PP; animated first transition from giant 3PP to controlling the character
Group 4.1: Control Multiple Characters Simultaneously - Share Same Environment		
Carly and the Reaperman [94]	control Reaperman (1PP) and Carly (3PP)	no switch
Moss [99]	control protagonist (3PP) and interact in 1PP	no switch
Astro Bot Rescue Mission [55]	control protagonist (3PP) and interact in 1PP	no switch
Trover Saves the Universe [119]	player (1PP) restrained to chair, controls a character (3PP), both are aware of each other	no switch
Down the Rabbit Hole [24]	control protagonist (3PP) and interact in 1PP	switch to protagonist (1PP) for dialogs, short fade
Medusa and her Lover [2]	control two characters (3PP)	switch to one character (1PP)
Group 4.2: Control Multiple Characters Simultaneously - Different Environmental Layers		
Pixel Ripped 1989 [8]	play a video game (1PP) and control the video game's character (3PP)	rise/lower the game console
Pixel Ripped 1995 [7]	play a video game (1PP) and control the video game's character (3PP)	second character visible on fixed screen in front of player
Golem [48]	protagonist (1PP) lies in bed and impersonates a golem in a dream world (1PP)	magic effect to blend realities

plots interweave at later stages. The orchestrated transition consists of a loading screen indicating the chapter title and next character. Finally, *DreamWorks Voltron VR Chronicles* [26] narrates a single multiprotagonist plot from a third-person view. For limited sections of the gameplay, players take the role of different characters from a first-person perspective. This transition happens automatically with a short fade to black.

Group 3: Separated Chapters. Whereas the first two categories used multiple protagonists in the same game environment, titles in the third group separate the different characters in multiple chapters. The experiences of these protagonists are connected to either each other or an overarching main plot. However, individual levels are limited to only one playable character. In *Contagion VR: Outbreak* [87], players experience a zombie apocalypse through various perspectives, accessible through the main menu. In *The Walking Dead Onslaught* [122], the players can join an NPC at a campfire, telling a story he encountered. After a black screen displaying the chapter title, the players can relive the story's plot from a first-person perspective.

The game *Asgard's Wrath* [108] combines multiple transition techniques between various game characters. The players take the role of a god, who possesses human heroes and assists them in their journey. The game features five playable main protagonists, whose stories are separated into chapters. Later stages of the game also permit switching between these heroes. Therefore, a loading screen displays a three-dimensional character model and a map marking the next position. Furthermore, players can use special altars in the game world to switch to their godly form and see their hero from a third-person view. Finally, new heroes are introduced with an animated transition from god mode to first-person perspective.

Group 4: Control Multiple Characters Simultaneously. The final category comprises games that do not switch between protagonists but allow players to control two characters simultaneously. We split this group into two subcategories to reflect the apparent difference in how the characters in these games relate to each other and the surrounding environment. In the first subcategory, both protagonists share the same environment and are aware of each other. The games *Carly and the Reaperman* [94], *Moss* [99], *Astro Bot Rescue Mission* [55], *Trover Saves the Universe* [119], and *Down the Rabbit Hole* [24] are constructed similarly. In all of them, the players take the role of a helpful ghost or giant who assists the main protagonist, seen as an often smaller third-person character. In contrast to the similar but not included game *Ghost Giant* [143], players of these games can interact themselves with the world and directly control the protagonist. Additionally, *Down the Rabbit Hole* [24] also switches the players' perspective for dialogs to a first-person view of the protagonist. In contrast to these games, *Medusa and her Lover* [2] grant the players direct control over the two main characters, seen from a third-person view. Players can switch to a first-person perspective for one of the characters at any time.

In the second subcategory, the two protagonists are not present in the same scene. Instead, these games split the environment into multiple layers. In *Pixel Ripped 1989* [8] and *Pixel Ripped 1995* [7], players embody a child in first-person perspective who plays a video game on a console. The players' attention is split between the happenings in the surrounding game world and the events on the console screen. The transition between both characters is done by turning towards or away from the game console. Similarly, the game *Golem* [48] tells the story of a protagonist lying in bed and impersonating a golem in a dream world. Players can trigger the transition between both worlds with a magic effect.

3.4 Summary of the Results

In general, these results show that currently published games with more than one main protagonist typically fall into one of three categories. Firstly, *in-scene transitions* are used to switch between protagonists in the same environment automatically or on-demand. Secondly, *chapter-based stories* split the plot into separate sections that are experienced from a single point of view. Finally, *multiperspective gameplay* allows players to control more than one character at a time by combining 1PP and 3PP or splitting the game world into layers.

Among these three categories, *multiperspective gameplay* is the most common technique in our sample. Even though it is an easily understandable concept, its potential for complex multiprotagonist plots is minimal. Players presume the identity of one protagonist from a first-person view while controlling another third-person character simultaneously. This design works well for puzzle games but is not suited for genres requiring ownership and identification with multiple characters of equal importance. Similarly, the *chapter-based stories* design excels at narrating individual extensive and separated storylines. However, it does not work with more frequent character transitions, like repeating events from a different perspective or switching between group members during the story.

Therefore, we focus on the third category, *in-scene transitions*, for the remainder of this paper. Such narrating techniques provide the basis for complex multidimensional stories, such as network or ensemble plots. Also, transitioning between different protagonists throughout the story offers a high potential impact factor. Players are already immersed in the story and are likely to be more responsive to getting to play contrastive characters. However, such game design choices also bear additional risks. The change in position and perspective could confound or disorient players, which is reflected in this review on the game *Araya* [79]: *"I found it was a little bit confusing to be jumping back and forth between the different character perspectives."* Furthermore, some of the analyzed titles used loading screens with additional information. The resulting break in gameplay might disrupt the players' flow and reduce presence.

4 DESIGNING CHARACTER TRANSITIONS

Switching between different playable characters with *in-scene transitions* can improve the gameplay experience and enrich the narrated story. However, a proper transition between protagonists should provide the necessary information about the new perspective without confusing the players or destroying the game's flow. Considering the novelty of this research area and the limited number of games using in-scene character transitions, we dedicate the remainder of this paper to exploring different transition techniques. Therefore, we start by establishing a set of common goals that characterize proper character transitions. Covering the entire design space of possible transition techniques would exceed the scope of this paper. Therefore, we focus on two different example implementations. The first concept combines elements from the analyzed games and displays an informative loading screen. The alternative technique is derived from prior work on locomotion techniques and an animated translation between both characters. With these exemplary concepts, we explore the potential of in-scene transitions for narrative VR games, identify open challenges, and reveal future research directions. Finally, we compare both concepts in an explorative user study.

4.1 Design Goals for Immersive Character Transitions

1. Preserve Presence and Flow. Abrupt cuts or visual artifacts draw the players' attention to the virtuality of the scenario and can reduce the perceived presence [85, 93]. Also, longer pauses in gameplay, such as loading screens, are likely to break the game's flow. Both effects are detrimental to the overall game experience and should be avoided.

2. Provide Transition Information. Past research has emphasized the importance of transition quality to maintain continuity between sections [141]. Consequently, players must not be disorientated and need minimal time to regain a complete understanding of the surroundings [61, 86]. In the context of character switches, we infer that the transition should provide complete information about the next protagonist, location, and context. Additionally, it might be favorable to include the character's previous actions for the sake of continuity [51].

3. Avoid Cybersickness. Automatic translational and rotational movements in virtual environments are likely to induce cybersickness [46, 84]. Therefore, developers of transition techniques must pay attention to this risk factor and stick to immediate teleportations or fast and short movements as these seem unproblematic.

4. Foster Perspective-Taking. Multiprotagonist plots are not meant to provide only gameplay variety. Instead, they should also enable players to experience a story from multiple, possibly contradicting, perspectives [34]. Therefore, transitions between characters should emphasize the identity change and encourage players to engage with the new body. Optimally, this experience leads to a sense of body ownership and an emotional response to the new character.

4.2 Character Transition Concept: Pause

For the first transition technique, we combined the most prevalent features extracted from the games in the previous step. Even the most direct cuts used a short fade animation to blend the two views. Additionally, some games display the next chapter title or character's name as text on a uniform background. *The Assembly* [91] also depicts a silhouette of the upcoming protagonist's upper body. The loading screen of the game *Asgard's Wrath* [108] is the most informative. Besides a small-scale character model, it also highlights the next level's position on a world map.

Based on these design elements, we constructed a first transition technique. Therefore, the players' view fades shortly to black before revealing an empty environment. The only element in the players' proximity is a top-down map of the game world, located 2.5m in front of the players (see Figure 2). On the map, a thick line leads from the next position in the world to a portrait of the upcoming character. Additionally, a text element displays the name of the protagonist. After a short pause of 7 seconds, the players' view fades again, and they are teleported to the next point of action. This transition design focuses on conveying the necessary data and feeling comfortable to the users. However, replacing the virtual environment with the overlay might also interrupt and disturb the players' flow.

4.3 Character Transition Concept: Animation

The second concept is meant to contrast the first design by avoiding clear cuts and nondiegetic interfaces. Instead, we aimed to convey the necessary information through perspective changes and a smooth animation between both characters. Therefore, we adapted a locomotion technique for large virtual environments called Outstanding [22]. The authors of this concept developed a smooth transition curve between a normal first-person perspective and an enlarged third-person view. Players could navigate their miniature character in this travel mode and switch back to 1PP for local interactions. According to the authors, this navigation concept benefits presence and spatial orientation without causing cybersickness. Additionally, the authors reported that participants had a more distant protector-protégé-relationship to their character in travel mode and experienced a feeling of possessing the avatar when switching to 1PP.

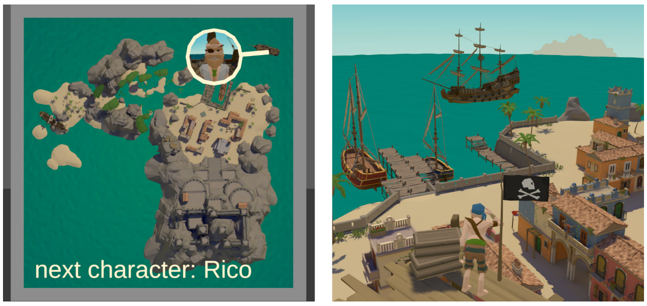

Figure 2: Our two presented character transition concepts. The left approach pauses the game and displays a map indicating the next character and location. On the right, the players' viewpoint switches to an enlarged third-person view before a quick forward translation is used to transport players to the next location.

We argue that the characteristics of the Outstanding technique suit our use case of character transitions: The elevated view height achieved by scaling the players grants an improved overview of the characters and their direct surroundings without requiring a map or interface. The smooth transition curve achieves the positional replacement without visible cuts or pause screens. Finally, the perceived disembodiment of the former avatar and possessing the next protagonist facilitates perspective-taking. Therefore, we constructed the second transition technique based on these design elements.

At first, the players experience an upscaling animation that switches from 1PP to 3PP and scales the players with a factor of 10 (see Figure 2). We used the transition curve and duration reported by the authors of the Outstanding concept. Next, a brief pause of 2 seconds allows players to take a last look at their old avatar. The transition between the two characters is a simple linear and fast forward translation that takes 1.5 seconds. Upon reaching the target point behind the new avatar, there is another brief pause of 2 seconds before the players transition back to 1PP with the same original Outstanding animation. Next, the players take the role of their new character and can resume the gameplay. The complete transition is with 7 seconds equally long as the pause concept. Another advantage of the animation is providing more context to the protagonists. For instance, the enlarged players could see the subsequent characters interact with the world before taking control over them.

5 EVALUATION

After implementing our two presented concepts for transitioning between protagonists, we conducted an explorative user study to compare both. Our evaluation process encompassed a mix of quantitative measures and qualitative feedback and was guided by the design goals established in the previous section. Therefore, we created a VR game featuring a short, interactive plot with multiple playable characters. Since lab studies were not possible at the time

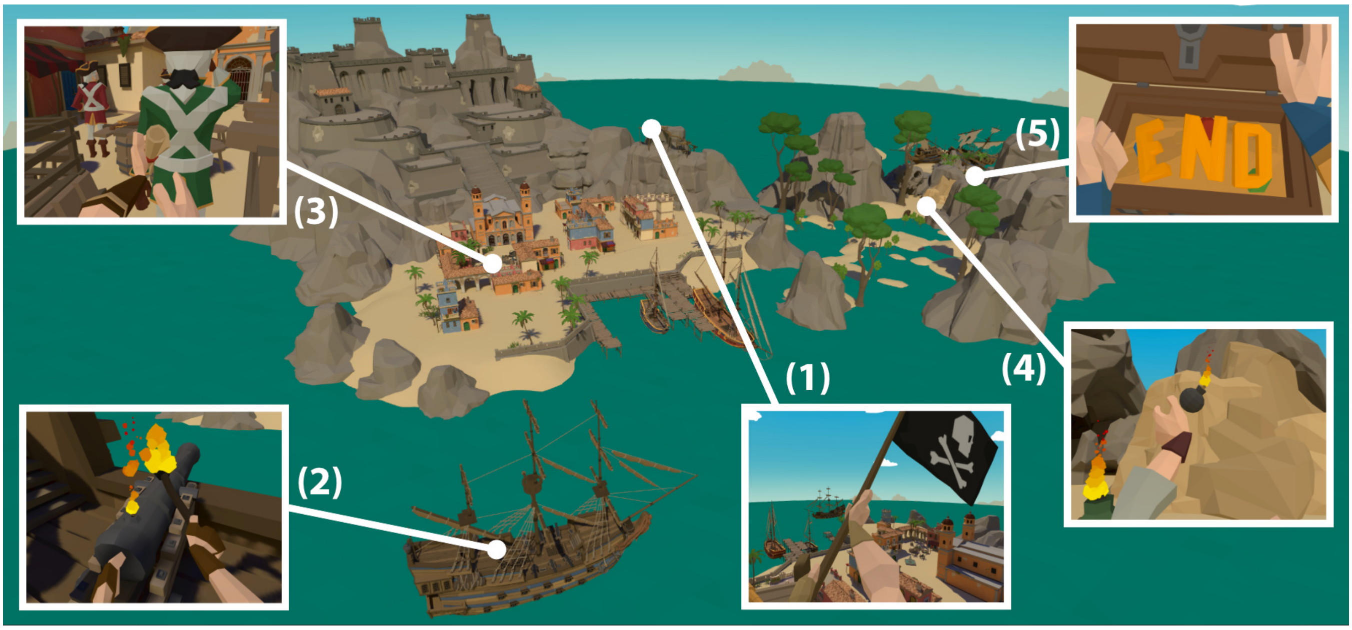

Figure 3: Overview of the test scenario, including all interactions players have to perform when controlling the various characters: waving a flag (1), firing a cannon (2), stealing a map (3), blowing up boulders (4), and opening the treasure chest (5).

of writing due to the COVID-19 pandemic, we decided to develop our application for the mobile Oculus Quest platform and execute the study remotely.

5.1 Research Questions and Hypotheses

The primary research goal for our study is to compare the two presented transition techniques and derive design considerations based on the participants’ feedback. Consequently, our research questions and hypotheses follow the previously established design goals for comprehensible and immersive character transitions. According to the first objective, it is essential to avoid interruptions in gameplay and preserve the players’ presence. In contrast to the pause screen replacing the players’ original view, the animated transition avoids visible cuts, so we assume a significant benefit to the perceived presence. The next goal is to provide a complete understanding of the character switch and connected relocation in the game world. Both developed concepts pursue different strategies: switching to an enlarged 3PP provides the players with an elevated view, whereas the pause screen uses a map interface as the information source. Without a clear superiority of either approach, we are interested in the differences regarding comprehensibility.

The third essential objective is to avoid inducing cybersickness. The first concept displays only a static interface and uses instant relocations. Therefore, we do not expect to detect any problems. Furthermore, prior research on dynamic perspective switching for locomotion purposes [22] has demonstrated that short and fast automatic translations are usually unproblematic. Consequently, we assume that neither of the two techniques induces notable cybersickness symptoms. Finally, the last established design goal is to emphasize the transition to a new avatar with a different body and identity. Considering the individuality of emotional responses towards the player character, we decided to focus on the experience of virtual body ownership as a reinforcing factor for identification [75]. Therefore, our last research question covers the differences in experienced IVBO between both concepts. In summary, our hypotheses and research questions are:

- H1: The two compared character transitions do not induce cybersickness.
- H2: The animated transition significantly increases players’ presence compared to the pause screen.
- RQ3: What are the difference between both concepts regarding players’ understanding of the character switch?
- RQ4: How do both transition techniques differ in terms of virtual body ownership?

5.2 Scenario

We implemented our VR game for comparing both transition concepts with the Unity game engine [130]. In the game’s plot, a pirate crew retrieves a treasure on a Caribbean island. The environment features multiple well recognizable points of interest. A fort towers above a small town with an adjacent port. Behind a small mangrove forest, another remote part of the island bears a shipwreck and the hidden treasure. Finally, a large pirate ship anchors just outside the port’s perimeter. We chose a low-poly design for the overall game as we targeted a mobile platform. The game is preceded by a main menu introducing the study’s context and controls. Afterward, the subjects take the role of the first pirate and receive instructions from the crew’s captain. Throughout the game, the subjects get to play all five crew members sequentially and at different locations in the game world (see Figure 3).

Table 2: Mean scores, standard deviations, and independent sample t-test values of the IGroup Presence Questionnaire (IPQ), the Virtual Embodiment Questionnaire (VEQ), and the Simulator Sickness Questionnaire (SSQ).

	Animation M(SD)	Pause M(SD)	$t(16)$	p		d	CI
IPQ (scale: 0 - 6)							
Spatial Presence	4.24 (0.78)	3.94 (1.15)	.871	.390		.299	$[-.394, .982]$
Involvement	3.47 (1.30)	2.84 (1.20)	1.477	.150		.507	$[-.240, 1.504]$
Realism	2.34 (1.11)	1.51 (1.11)	2.163	.038	*	.742	$[.048, 1.599]$
General	4.06 (1.30)	3.41 (1.33)	1.438	.160		.493	$[-.269, 1.564]$
VEQ (scale: 0 - 6)							
Acceptance	3.41 (1.20)	2.38 (1.58)	2.139	.040	*	.734	$[.049, 2.001]$
Control	4.56 (1.07)	4.10 (0.87)	1.363	.183		.467	$[-.226, 1.137]$
SSQ (scale: 0 - 3)							
Nausea	8.98 (15.63)	2.81 (5.61)	1.533	.141		.526	$[-2.030, 14.376]$
Oculomotor	9.81 (14.37)	5.80 (8.27)	.998	.326		.342	$[-4.180, 12.206]$
Disorientation	21.29 (31.58)	6.55 (11.13)	1.816	.084		.623	$[-2.196, 31.673]$
Total	14.08 (20.16)	5.72 (8.06)	1.587	.127		.544	$[-2.592, 19.312]$

$^{*}p < .05$, $^{**}p < .01$

Each played character differs in appearance and voice and features a unique interaction. After spotting a target with a spyglass and waving a flag, the subjects get to fire a cannon, steal a treasure map, throw bombs to blow up boulders, and open the treasure chest. Each character reminds the subjects of their current task by speaking to themselves. As one of our goals is an increased feeling of body ownership, we use full-body avatars for the protagonists. Therefore, we track headset and controllers and animate the body through inverse kinematics. After completing all tasks for one protagonist, the game initiates a character transition automatically. Depending on the study condition, either the pause or the animation concept is used. The scene fades upon opening the treasure chest, and the subjects return to the main menu.

5.3 Procedures and Applied Measures

We conducted a remote between-subject study to answer our research questions and validate our hypotheses. We chose this step as in-person lab studies were impossible due to high COVID-19 incidences. Instead, we built the VR game for Oculus Quest [39] and distributed it through various platforms, including Oculus AppLab [38], a download link of the apk-file, and a SideQuest listing [111]. Additionally, some subjects were recruited through personal contacts.

After starting the application, subjects received an in-app briefing informing them about the overall procedure, the general study's goals, and the controls required for playing the game. We decided to make study participation optional at this stage. Also, the app did not collect any data because available metrics, such as gameplay duration, possess little explanatory value. If subjects agreed to participate, they were randomly assigned to one study condition and continued to play the main game. After completing the final task by opening the treasure chest, subjects returned to the main menu and received the survey link and a condition-depending access code. After filling out the main questionnaire, subjects could optionally return to the app to replay the game with the alternative transition concept.

The study's questionnaire consisted of multiple parts. After entering the access code and answering three elementary comprehension questions, which we used to filter incomplete participations, subjects were asked to provide basic demographics, i.e., age, gender, and VR gaming habits. Next, we included two tasks where subjects had to arrange images in the correct order. The first displayed pictures of the played characters, whereas the second showed maps depicting the visited points of interest. We aimed to test the subjects' understanding of the character switches and relocations with this task. As we were interested in the differences in the perceived presence (see H2), we administered the IGroup Presence Questionnaire (IPQ) [110], containing a single item on *general presence* and the three subdimensions *spatial presence*, *involvement*, and *experienced realism* (all coded 0 - 6). Furthermore, we used the Simulator Sickness Questionnaire (SSQ) [58] to test our hypothesis H1. The SSQ consists of the three subscales *nausea*, *oculomotor*, and *disorientation* (rated 0 - 3). For RQ3, we administered two Virtual Embodiment Questionnaire (VEQ) [105] subdimensions: *acceptance* and *control* (coded 0 - 6). Finally, we concluded with 6 custom questions (coded 0 - 6), covering additional aspects related to the character transition. Before finishing the questionnaires, subjects were given two optional text fields for additional feedback regarding their experience and the replay with the alternative concept.

6 RESULTS

In total, 34 persons (10 female, 23 male, 1 non-binary) with a mean age of 33.76 (SD=15.79) participated in our study. Despite mainly recruiting subjects owning VR headsets, most participants reported playing VR games only rarely (41.2%) or sometimes (32.3%). Only a minority of 26.5% stated they were playing VR games frequently or every day. As we applied a between-subject study design, we compared the evaluated measures between both conditions with independent sample t-tests. Therefore, we first ensured the test's

Table 3: Mean scores, standard deviations, and independent sample t-test values of the custom questions (CQ).

Question Item		Animation M(SD)	Pause M(SD)	$t(16)$	p	d	CI
CQ1	After playing the game, I had a good impression of the different locations in the game world.	4.88 (0.86)	3.24 (2.14)	2.949	.008**	1.012	[.486, 2.808]
CQ2	I could orient myself well in the game world.	4.94 (0.97)	3.12 (2.00)	3.390	.003**	1.163	[.711, 2.936]
CQ3	After each character switch, I needed a moment to orient myself.	3.00 (2.18)	3.59 (1.91)	-.838	.408	-.287	[−2.019, 0.842]
CQ4	I perceived the character switch as disturbing.	1.82 (1.63)	2.35 (1.97)	-.855	.399	-.293	[−1.791, .732]
CQ5	I perceived the character switch as confusing.	2.59 (1.62)	2.53 (1.81)	.100	.921	.034	[−1.14, 1.259]
CQ6	Switching between multiple characters improved the game experience.	4.12 (1.11)	2.88 (1.50)	2.734	.010*	.938	[.315, 2.156]

$^*p < .05$, $^{**}p < .01$

assumptions by testing for homogeneity of variances using Levene’s and normal distribution with Shapiro-Wilk tests. If the data did not meet the requirements, we instead used Mann-Whitney U tests. The following section reports the significant differences between conditions, together with the effect strength and the confidence interval. We executed all listed calculations with IBM SPSS 27 [52].

6.1 Questionnaires

To detect potential cybersickness effects and confirm our hypothesis H1, we assessed the SSQ. Whereas the subscale’s means for the animated transition are higher than the low scores for the pause condition, they do not indicate a statistically significant difference (see Table 2). Also, the scores correspond to the values reported by Cmentowski et al. [22] for the original Outstanding study that were considered negligible. Furthermore, we assessed the IPQ to explore the transitions’ effects on the perceived presence. All subscales have a general tendency in favor of the animated transition, although only the means of the realism subscale differ significantly with a medium to large effect. Finally, we administered two subscales of the VEQ to answer our fourth research question regarding the experience of body ownership. The acceptance subscale reveals a medium to large significant effect in favor of the perspective-switching animation.

6.2 Custom Questions

Apart from using standardized questionnaires, we included two tasks to test the subjects’ understanding of the game’s plot. Therefore, subjects had to arrange pictures with the different characters and visited locations in the correct order. To quantify the correctness of the subjects’ answers, we calculated the inversion number, which is a standard measure for the sortedness of a sequence. For the character-sorting task, subjects made 1.7 to 2.1 errors on average: $Inv(char)_{animation} = 1.706$ (SD=2.085), $Inv(char)_{pause} = 2.118$ (SD=2.522). This difference is not statistically significant ($t(32) = -.519; p = .607; d = -.178$; 95% $CI[-2.028, 1.205]$). We could also observe similar results for the second task: $Inv(map)_{animation} = .765$ (SD=1.437), $Inv(map)_{pause} = 1.882$ (SD=2.233). Whereas subjects in the animation condition made fewer mistakes, this difference is also insignificant ($t(16) = -1.735$; $p = .092$; $d = -.595$; 95% $CI[-2.430, .194]$).

Finally, we also administered multiple custom questions to evaluate the subjects’ personal opinions on specific characteristics of the transition concepts. These questions covered spatial orientation (CQ1, CQ2, CQ3) and potential effects of the character transitions on the game experience (CQ4, CQ5, CQ6). The results for all questions are shown in Table 3. Of these questions, the items CQ1 and CQ2, measuring the orientation in the game world, indicate large to very large significant effects. It appears that subjects gained a better understanding of their surroundings when using the perspective-switching concept. Also, the large effect in CQ6 reveals that especially subjects in the animation group felt that the multiprotagonist plot improved their game experience.

7 DISCUSSION

Apart from using the quantitative study data, we also collected qualitative feedback from the subjects. Therefore, we included two optional text fields at the end of the survey to provide enough space for comments on the assigned transition technique and the comparison in case subjects played the replay. Two-thirds of the subjects used this opportunity, providing additional input for discussing and contextualizing our research questions and hypotheses.

H1: The two compared character transitions do not induce cybersickness.

The results of the SSQ do not differ significantly between conditions and also fall within the range of prior studies [22]. Thus, it appears that at least the subjects of our experiment did not suffer severely from cybersickness symptoms, which confirms our hypothesis H1. However, the subscale’s means for the animation condition still exceed those of the other group by a factor of two to three. Whereas not statistically relevant, this finding might still hint at a more severe problem. Multiple subjects noted their concern that the animated transition could potentially lead to cybersickness for other people: *"I expect some players to experience VR sickness if they are not prepared for the animation, though I had no issues"(**P7**). "I have never gotten sick during VR but my dad does often, so depending on the game itself you might want to go with a more polished version of the map"(**P25**).* Inexperienced players in particular might be affected: *"The transitions were very fast, and I expect the movement would disorient newcomers"(**P6**).*

Considering this feedback, we see the necessity for further research and improvements of the used animation. Compared to past research on using dynamic perspective switching for long-distance locomotion, our collected feedback is less positive. We suspect a potential reason in the combination of the vertical transition between 1PP and 3PP and the quick forward translation. Concatenating these movements might introduce a potential source of disorientation. Whereas participants suggested *"a very slow move into the next character"(**P6**)* as a possible solution, previous research has demonstrated that slow automatic movements increase the risk for cybersickness even more [46, 84]. Instead, we recommend further research on alternative approaches, such as using teleportation instead of a forward translation.

H2: The animated transition significantly increases players' presence compared to the pause screen.

Our second hypothesis, H2, presumed that the continuous animation, which avoids interruptions in the visual flow, would significantly increase the players' presence. Only the realism subscale confirmed our hypothesis partly by indicating a significant advantage of the animation condition to the experienced realism of the virtual environment. Additionally, many subjects emphasized the disturbance in flow when pausing the game and displaying the map: *"The map interrupts the gameplay much more."(**P15**)*. In contrast, the animation concept was considered more appealing (*"I think the [animation] technique was more interesting in terms of aesthetics."(**P4**)*) and less interruptive (*"The animation is way better than the transition; the latter is too jarring and cuts the flow of the story."(**P2**)*). Another comment concerns the automatic invocation of the character transition, which we based on implementations in similar games [26, 79, 91]: *"It also felt very directed; I had no control over when to change"(**P2**)*. This feedback indicates that players might feel limited in their autonomy. Therefore, we propose using player-controlled transitions in future studies.

RQ3: What are the difference between both concepts regarding players' understanding of the character switch?

The primary goal of every character transition technique is to convey an accurate impression of the actual switch, the next played avatar, and the changed location. Our two concepts use different approaches to achieve these targets. The pause technique displays a top-down map with a marker for the next character and position, whereas the alternative approach relies only on the players' perception of their virtual surroundings. We did not formulate a strong hypothesis but tested for the above-mentioned qualities with two ranking tasks and six custom questions. Three custom questions, CQ1, CQ2, and CQ6, depict a significant difference and reveal that subjects in the animation group believed their condition was *"much better for spatial perception"(**P13**)* and enhanced their game experience. Other feedback confirms this positive effect: *"Initially, I found switching characters a bit confusing, but later on I thought it helped me to understand the game environment"(**P4**)*, *"I started using the map, compared to animation it felt lackluster. The animation was cool because it let you see the characters and it felt smoother."(**P25**)*.

Even though we did not measure adverse effects on character identification, some responses indicate a potential drawback: *"The animation felt much more immersive and improved my understanding of the relocations. However, I had more problems identifying the next character."(**P7**)*. By combining both techniques into one concept, one could benefit from these individual strengths: *"I would prefer a mix of both techniques, where the players choose the next character on a map before experiencing the transition animation"(**P7**)*. In general, the overall medium scores for reorientation time (CQ3), disturbance (CQ4), and confusion (CQ5) still emphasize the need for further improvements of both concepts.

RQ4: How do both transition techniques differ in terms of virtual body ownership?

Our final research question dealt with the transitions' effects on the experience of owning a virtual body. This sensation can greatly improve the game experience and foster perspective-taking. However, most previous research only tested virtual body ownership for one single avatar. Therefore, we did not formulate any prior hypothesis regarding the measured VEQ scores for our study. Nevertheless, the resulting scores for both conditions are relatively high, and indicate a significant difference for the acceptance subscale in favor of the animation concept. The discrepancies between the subscales acceptance and control might be explained by the artistic low-poly style of the game, reducing the level of realism. Similar to qualitative feedback reported by Cmentowski et al. [22] for the original Outstanding concept, one participant stated: *"It felt like I was possessing people rather than being them, but it was fun"(**P2**)*. This feedback suggests an incomplete body ownership sensation that might be worth investigating in future studies. Also, some subjects criticized the pause concept for being less suited for gaining a good impression of the played character: *"I didn't really have any reinforcement after the quick character switch as to who I was or what I looked like"(**P9**)*.

8 LIMITATIONS

With our research, we took the first steps into the primarily unexplored field of multiprotagonist storytelling for VR games. Of course, exploring the entire design space of immersive character transitions in the scope of one paper was impossible. Consequently, we focused on the highly promising *in-scene transitions* as a requirement for complex intertwined narratives involving multiple main protagonists. However, we emphasize the importance of additional future research on the other categories, *multiperspective gameplay* and *chapter-based stories*. Furthermore, we selected two interesting and opposing transition concepts we compared in our study to reveal open challenges and future research directions. Even though we carefully justified our choice, many other transition techniques are worth a closer look. Even for our investigated methods, a lot of open questions remain, such as the influence of different pause durations on the player experience.

Apart from limiting ourselves to only one category of transitions, we also had to consider the restrictions imposed by the COVID-19 pandemic. Our evaluation of the local circumstances led to our decision to replace the usual lab study with an online experience. In particular, this study design impacted our research process in two areas. Firstly, we had to limit the questionnaires to the absolute minimum to encourage external players to participate. As a result, we tested for spatial orientation only through custom questions. Other measurements would have been preferable for a better understanding, such as pointing or map-drawing tasks. Secondly, we did not collect any data from the VR application directly. This decision eased our data collection policy and the strict app-publishing process. However, as our only data came from the questionnaires, we do not have any insights on aspects such as task competition time or overall success rate.

9 CONCLUSION AND FUTURE WORK

Storytelling allows us to perceive the world from other perspectives than our limited point of view. This storytelling experience can be reinforced by actively including the audience in interactive games or even letting them become a protagonist in immersive virtual environments. Whereas films, novels, and also increasingly games narrate complex multiprotagonist plots, VR games often remain centered around one single character. In our work, we addressed this unused potential by taking a closer look at the design of immersive and natural transitions between different avatars. Therefore, we first identified VR games with more than one protagonist and categorized them according to their transition concept. Next, we established design goals for better character transitions and developed two concepts based on our analysis and prior research. A final user study revealed that both techniques have unique strengths and weaknesses, such as improving spatial orientation or providing easily comprehensible information. In summary, our work introduces this novel research field and demonstrates the importance of additional work to achieve believable and complex narratives for future VR games. In future research, we will deepen our understanding of multiprotagonist plots in virtual scenarios and further improve and refine the existing concepts to achieve an optimal transition between characters.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put…": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	**Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives** *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives

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Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives

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Figure 1: Our research compares two common perspectives used to deliver VR gaming content: using the player's view as a first-person perspective (left) versus a third-person mixed-reality view blending the player into the virtual world (right).

ABSTRACT

The spectatorship experience for virtual reality (VR) games differs strongly from its non-VR precursor. When watching non-VR games on platforms such as Twitch, spectators just see what the player sees, as the physical interaction is mostly unimportant for the overall impression. In VR, the immersive full-body interaction is a crucial part of the player experience. Hence, content creators, such as streamers, often rely on green screens or similar solutions to offer a mixed-reality third-person view to disclose their full-body actions. Our work compares the most popular realizations of the first-person and the third-person perspective in an online survey ($N = 217$) with three different VR games. Contrary to the current trend to stream in third-person, our key result is that most viewers prefer the first-person version, which they attribute mostly to the better focus on in-game actions and higher involvement. Based on the study insights, we provide design recommendations for both perspectives.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; • **Software and its engineering** → **Interactive games**; Virtual worlds software; • **General and reference** → *Empirical studies.*

KEYWORDS

virtual reality, spectator, games, streaming, perspective, first-person, third-person

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1 INTRODUCTION

Ever since the establishment of live streaming platforms such as Twitch [1], watching other play became a popular spare-time activity across all ages. The digital audience tunes in for various reasons, be it to follow an esports tournament or to check out a newly released, trending game. This curiosity also applies to recent virtual reality (VR) titles (cf. *Half-Life: Alyx* [46]), forcing streamers to adapt their content creation and delivery pipeline to the specifics of VR.

The main difference is that VR games heavily rely on the high degree of immersion provided by such stereoscopic setups. The player experiences a feeling of being in the virtual world, which is usually achieved by the head-orientation-dependent view in combination with realistic full-body interactions. Clearly, that impression cannot be easily transferred to the audience, because most spectators utilize 2D displays, e.g., mobile devices or PC/TV screens. Hence, streamers seek for viable non-VR workarounds to deliver the immersive VR gaming content.

One prominent way to transport the experienced presence to the audience is to provide a mixed-reality view of the player/streamer. By switching to a third-person perspective, the player blends into the surrounding virtual environment. The spectators can see the player's full-body movements and interactions in context, enabling a better understanding of the actual gameplay experience (see Figure 1).

On the other hand, the traditional first-person perspective offers a unique advantage: seeing the game from the player's perspective brings the spectators as close to the in-game action as possible. Due to the same point of view, the spectators obtain identical visual information. This similar visual perception of the virtual world can potentially evoke the viewers' feeling of playing on their own.

So, which perspective is best for the streaming of VR games? Given the aforementioned conceptual differences and the fact that both perspectives are widely used and accepted, we do not expect a definite answer to this question. The right choice of perspective seems to depend on different contextual factors, such as the type of the game or the purpose of watching. Hence, there is a need to study spectators' preferences and motives in different contexts to support the creation of compelling audience experiences.

With our work, we lay the foundations for the research of spectator experiences and perspectives in VR settings. The choice of perspective significantly frames the viewing experience. While researchers agree that immersion is an important part of interactive VR experiences, it remains unclear how important immersion is for spectators of VR players compared to other factors such as contextual understanding and player centricity.

Aiming towards a comprehensive VR streaming guideline, our work is the first to contribute relevant insights into spectators' opinions. We present an online survey (N = 217), which covered three different VR games: *Beat Saber* [2], *Superhot VR* [42], and *Stand Out: VR Battle Royale* [31]. For each game, the spectators watched a first-person and a third-person video and finally shared their impressions. The so obtained results allow us to discuss each perspective's particular strengths and weaknesses and formulate preliminary design considerations, which are meant to provide a starting point for VR content creators.

We have to understand how different perspectives (such as first-person and third-person) contribute to different demands of spectators to be able to make informed design choices. This research is not only relevant in the context of game streaming. It also applies to related VR setups including some kind of spectator. In particular, the choice of perspective is important in multi-user scenarios that combine VR and non-VR users. Example scenarios include VR training applications (surgical training, rehabilitation games) where the perspective choice is crucial for supervisors to be able to adequately monitor and evaluate the trainee's performance. Hence, apart from giving practical advice to VR streamers and content providers, our work creates the basis for more sophisticated choices of perspective and paves the way for future research on audience experiences in VR.

2 RELATED WORK

Today, online video and streaming platforms such as YouTube [54] and Twitch [1] enable a globally distributed audience to watch their favorite players and games at any time. Former consumers can now easily produce user-generated content (UGC) and are challenging the traditional media [5]. So-called *Let's Play* videos have become increasingly popular [14] and game live streaming has become a cultural phenomenon comparable to sports events [18, 29, 41]. Apart from casual gaming videos, competitive gaming events, commonly referred to as esports [17, 30], are taking a growing share of the overall streaming landscape [8].

Considering the overall popularity of game streaming, the motives and experiences of spectators have been of ongoing interest to the games user research community [21, 43, 50]. Instead of just focusing on the experience of the active player, a variety of work has broadened the research scope by explicitly investigating the spectator experience [4, 11, 13, 28, 44] and the motivations for viewers to spend their free time watching others play [10, 18, 24]. The spectator's experience is influenced by the game content, but also by the spectator interface [32], that is the available information and the perspective from which they view both the game and the player. Moreover, spectators—no matter if co-located or mediated—are part of the social play setting and often engage in some form of interaction with the player, which further shapes their experience [12, 18, 44, 48].

This social interaction is also a strong motivator for watching game streams [18]. Other vital factors are enjoyment, information seeking, and distraction [6, 18, 24]. For esports, research has revealed two additional motivators: the general competitive atmosphere and the opportunity to share emotional connections [17, 26, 38, 51, 52]. Hence, the reasons why spectators watch Let's Play videos and game live streams seem manifold. A commonly used framework to assess the motivation behind media usage is the *uses and gratification* (UG) model [22, 23, 33, 34]. UG is based on the assumption that users actively choose certain media with the motivation to achieve a particular gratification. The available media has to compete constantly with other sources of gratification, and personal reasoning is considered individually for every user. UG typically classifies the user needs into the categories *cognitive, affective, personal integrative, social integrative, and tension release.* In an empirical study, Sjöblom et al. [39] revealed that all five classes of gratification are associated with the motivations of twitch users watching game live streams.

The previous research on game videos and streams is mainly based on the footage of common, non-VR games. VR games have just recently gained a foothold in the consumer market. New hardware and the release of sophisticated AAA-games, such as *Half-Life: Alyx* [46] and *Asgard's Wrath* [37], have led to regular media coverage and an increased interest of the broad gamer community. In contrast to non-VR games, the special setup of VR games including head-mounted displays (HMDs) and movement tracking makes it more challenging to convey the entire immersive experience to spectators. In particular, the player's body movements used to control the game become an integral part of gameplay. Research dealing with the audience of VR games remains sparse and is mainly focused on local spectatorship [16, 19, 20, 25, 53]. Hence, the questions remains how the game experience can best be delivered in videos and streams to a broad online audience.

One possibility is to use the same approach as with non-VR games: players directly broadcast the game view that is displayed on the HMD, so that the audience sees the same as the player. This first-person perspective ensures that the spectator's focus always matches the player's current focus and that the spectators see the game world as if they were playing themselves. Research on different player perspectives indicates that a first-person view makes it easier for players to focus on the action and provides advantages to immersion [9, 49]. These effects might also apply to the spectator's perspective.

On the other hand, a first-person streaming perspective does not show the player's bodily interaction with the VR game. This might impede a full understanding of what is happening, as the manipulations conducted by the player are partly hidden from the spectator and only the effects in the game are revealed [32]. Tekin and Reeves [44] point out that seeing the game on screen and at the same time seeing the player's bodily actions—resulting in a "dual vision"—are important parts of spectating. Therefore, many VR game streamers follow a different approach by providing a third-person perspective: they use a green screen and external cameras to blend themselves into the virtual world (similar to the original trailer of the HTC Vive [45]). This mixed-reality perspective enables spectators to see the game world and the player at the same time, and might thus enhance their experience. At the same time, this approach creates a mismatch between the spectator's view and the player's view. Consequently, the third-person perspective underlines the difference between player and spectator and shifts the focus of spectating from events in the game world to the player.

As both perspectives seem to have advantages and shortcomings, the question arises how spectators experience and evaluate the different views and which perspective is superior in certain contexts. To the current date, there is no other work investigating this open research question. While there are some related studies on the use of different user perspectives in VR environments [7, 15, 36, 40], these are not directly applicable to the experience of spectators.

Figure 2: *Beat Saber* [2] is one of the three games used in the online survey. Participants compared two perspectives: first-person (top) and third-person view (bottom).

3 ONLINE SURVEY

We conducted an online survey to assess spectators' preferences and opinions on the different perspectives in VR game videos. More precisely, we compared the first-person perspective, which directly displays the in-game view of the player, with a mixed-reality third-person perspective, in which the player is captured and directly cut into the game world (see Figure 1). The goal of the study was to gain insights about the advantages and disadvantages of both approaches regarding different aspects of the viewing experience such as comprehensibility, entertainment, and involvement. Hence, our main research question is how spectators experience the two perspectives, which differences can be found, and which perspective is preferable in certain settings.

3.1 Selection of Three Exemplary VR Games

We decided to compare the two perspectives using different commercial VR games, as viewers' preferences and experiences may also depend on certain characteristics of the game. Our game selection process was based on several criteria. First, the games should be popular and positively rated, to ensure that they provide an interesting experience and successfully make use of VR headsets. Second, the games had to support the software tool LIV [27], which enabled us to create the mixed reality third-person perspective. Finally, the games should represent different game genres, which feature different core mechanics and controls. Following these criteria, we reviewed the rankings of current VR games on the online gaming platform Steam [47] and analyzed viewer numbers on Twitch to identify popular games. We chose three games that match all criteria: *Beat Saber* [2], *Superhot VR* [42], and *Stand Out: VR Battle Royale* [31] (hereafter abbreviated as *Stand Out*). All games had more than 25.000 peak viewers on Twitch and more than 1.000 mainly positive reviews on Steam, indicating their popularity.

Figure 3: *Superhot VR* [42] is one of the three games used in the online survey. Participants compared two perspectives: first-person (top) and third-person view (bottom).

Figure 4: *Stand Out: VR Battle Royale* [31] is one of the three games used in the survey. Participants compared two perspectives: first-person (top) and third-person view (bottom).

Beat Saber is a music-based VR game. The player chooses a song and then swings two colored lightsabers to cut blocks of the same color, which represent the beats of the music and quickly approach the player (see Figure 2). Hence, the main focus of the game is on the quick gestural reaction of the player to the fast-paced blocks. There is a direct mapping between the player's hand movement and the movement of the lightsabers in the game. Apart from single steps to the side to avoid an obstacle wall, there is no locomotion needed. As the blocks always approach on fixed paths in front of the player, the view orientation in *Beat Saber* is rather fixed. We chose this game due to its remarkably high popularity, and because in current *Beat Saber* streams, both perspectives we want to compare (first person and third person mixed reality) are commonly used.

In *Superhot VR*, the player has to complete short levels by destroying all enemies and dodging their attacks (see Figure 3). For this purpose, the player can use various objects lying around, such as pistols and bottles. The unique twist of this game is that time progresses only at the speed in which the player moves. That means, if the player moves slowly, the enemies also move slowly, and vice versa. This way, the player has to consider every movement, resulting in rather slow-paced gameplay. Though the player can move in room-scale, the enemies are then approaching quickly. So in most levels, there is not much locomotion happening, and the focus is on the opponents. However, enemies are approaching from different sides, so that the perspective is not fixed in contrast to *Beat Saber*.

Stand Out is a first-person shooter in which the player plays online against a large group of other players (see Figure 4). Following the battle royale principle, the goal is to be the last survivor on the island where the game takes place. To win, the player has to collect weapons and ammunition, shoot other players, and move across the island. The player can travel larger distances using the control stick. Hence, in contrast to the other two games, locomotion is very prevalent in *Stand Out*. Like in other first-person shooters, the gameplay is rather fast-paced in general. The focus of attention is very dynamic since the player has to react quickly in case of an attack.

All in all, the three games differ mainly concerning pace, focus, and locomotion. We assume that these characteristics can potentially influence the spectators' experience in the two perspectives under investigation, as these provide different main focal points. For instance, quick game events might be more comprehensible for spectators if they see both the player and the game world in the third-person mixed-reality perspective. On the other hand, the first-person perspective might be more suitable for games with a dynamic focus and much locomotion. Therefore, we included all three games in both perspectives in our study to investigate potential differences.

3.2 Implementation of the Different Perspectives

Overall, there are several possibilities to compile a stream of a VR gaming session. We decided to compare two basic approaches which are commonly used by streamers and at the same time differ significantly regarding their main focal point: the first-person view and a mixed-reality third-person perspective. While some streamers also use a combination of different views by compiling picture-in-picture modes, we focus on the two main approaches, as we are particularly interested in how spectators evaluate the possibility to see the player integrated in the game world in the third-person view and the lack thereof in the first-person view.

As stated above, we recorded two gameplay videos for each of the three games: one with the first-person perspective and one with the third-person perspective. In all cases, the same player (male, 26 years old) played the game and all videos are about three minutes long.

The first-person view was simply a screen-recording of the game from the player’s point of view. To create the third-person mixed-reality views, we used the software *LIV* [27], which allows integrating a green screen recording of the player into the game world. We used an additional, static game camera to capture the game scene from behind the player (cf. Figures 2, 3, and 4). We also considered rotating the mixed-reality camera dynamically based on the player’s actions. While this approach is technically possible using *LIV*, it requires a far more sophisticated setup. Since a dynamic camera was not required to address our main research question and since we wanted to stick to the most commonly used techniques in the gaming community, we discarded this option. Instead, we tested different positions while implementing the third-person views to find an appropriate static camera position for each game.

LIV also enables to replace the real player by an avatar model, a feature used by some streamers, as well. However, such a third-party avatar is not visually matched to the game and, thus, introduces an additional source of interference. While the real player’s appearance also mismatches with the game world, a mixed-reality view best reveals the manipulations conducted by the player in the direct context of the game. For these reasons, we decided to not use a virtual avatar.

3.3 Study Plan and Survey Structure

We conducted a mixed design online study with the game shown in the videos as a between-subjects variable and the video perspective as a within-subjects variable. That means, each participant was randomly assigned to one game and watched both videos of that game. The order of the two perspectives was counterbalanced, as well, to avoid bias due to potential sequence effects.

The survey started with a short introduction, informing participants about the goal, procedure, and anonymity of the study. Then we asked for basic demographic data, including age, gender, and nationality. Additionally, we requested some information about participants’ familiarity with VR headsets and VR games, as well as their digital gaming and streaming habits.

As we were also interested in viewers’ general motivations to watch videos or streams of VR games, we compiled a list of possible motives based on the uses and gratification theory. More precisely, we derived our items from the work of Sjöblom et al. [39], who investigated the motivation of Twitch users. Although this motivational model does not explicitly refer to VR streaming content, we believe that the general types of motives of viewers are largely independent from the platform used by the streamer (including VR setups). Hence, we think the model includes all high-level motivations that are relevant in the context of our study. The question and the final list of answers can be found in Table 1. Participants were asked to select all reasons that apply (multiple answers were possible). We also included the option *"None (I would not watch a video of a VR game)"*, to be able to identify participants having no interest in the study’s topic.

Following this first, general part of the questionnaire, we asked participants to ensure that their speakers or headphones are active to be able to hear the sound of the videos and then showed them the first video. To control that the video was not forwarded or skipped, we measured the time participants spent with the video. This way, we were able to identify participants who skipped (parts of) the videos and label their data as invalid.

After the video, we administered the enjoyment subscale of the Intrinsic Motivation Inventory (IMI) [35] to assess how much participants enjoyed watching the video. To further investigate the viewing experience, we asked additional custom questions about the view and the comprehensibility of the video, as well as the perceived involvement. The full list of questions can be found in Table 2. Then the second video was shown, and again IMI and the custom questions were administered after that. Then, we asked whether participants knew or have played the game shown in the videos before, how much they like the game and how much they like the genre it belongs to in general. Finally, participants were asked which of the two perspectives they preferred. There was also the option to indicate that they did not have a preference. In a free-text form, we asked participants to give reasons for their decision. Moreover, participants could provide any additional notes.

Considering that we cannot completely control the setting and conditions under which participants take part in an online study, we increased the validity of the data by including sanity check questions. For this purpose, we asked the same question twice with reversed scales, to ensure that participants have read the question text and did not select random answers.

3.4 Recruitment and Sample

We were interested in the opinion of potential spectators of VR game videos and aimed at improving their viewing experience. Thus, we defined all persons who have at least some interest in VR technology and digital games as our target group, with no further restrictions regarding demographic data or prior experience with VR. We promoted the survey on different online channels, both in English and in German. That included several Reddit communities and Facebook groups related to the topics game streaming or VR games. Moreover, we also used more general groups that are aimed at the recruitment of online survey participants.

In total, 316 participants completed the survey. Sixty-nine of these cases had to be excluded from the analysis because participants failed the sanity check questions or did not watch the videos completely. Moreover, we excluded 30 additional participants, who

Table 1: Overview of the different motivational aspects related to the viewing of VR game videos (participants were asked to select all answers that apply).

Class of Gratification (based on Sjöblom et al. [39])	Which of the following reasons could motivate you to watch a video where a player is playing a VR game?	Votes (N=217)
cognitive	to inform me about the game or to get an impression of it (*information seeking*)	113
cognitive	to learn new game strategies or how to master the game (*learning game strategies*)	84
affective	because it is entertaining and/or exciting (*enjoyment*)	119
personal integrative	to be able to comment and have a say (*recognition*)	24
social integrative	in order not to feel alone (*companionship*)	26
tension release	to distract me and pass the time (*distraction*)	62
tension release	in order to relax (*relaxation*)	46

stated that they had no interest in VR games and would never view videos of such games voluntarily. Those participants do not match our target group. Hence, our final sample contains 217 participants.

The sample includes a wide variety of nationalities (27 different countries), with 63 German and 77 American participants being the majority. The mean age of participants was 28 (SD = 8.69), with a range from 16 to 64. Regarding gender, the sample included 125 male and 92 female participants. About three-quarters of all participants (N = 172) reported that they regularly played digital games. Many participants also had prior experience with VR games, with only 58 persons stating that they have not yet used a VR headset. Regarding the question how often they watched gaming videos/streams on average, most participants (N = 189) reported that they watched game streams at least once a month.

Concerning our three game subgroups, the distribution is a bit uneven: 89 participants viewed the videos of *Superhot VR*, 67 participants viewed *Beat Saber*, and 61 *Stand Out*. However, the distribution of age, gender, and nationality is comparable among the three groups. About two thirds of the participants in the *Beat Saber* group knew the game before (N = 44) and nearly half of the group had played the game themselves (N = 29). *Superhot VR* was known to half of the participants (N = 40) and 33 participants had played the game. *Stand Out* was less known by our participants, with only 13 persons being familiar with the game, of whom 8 had played it. Asked about how much they liked the game, participants in all three game groups rated the games slightly positive on average on a scale from 0 to 6 (Beat Saber: M = 4.19, SD = 1.79; *Superhot VR*: M = 3.53, SD = 2.07; *Stand Out*: M = 3.15, SD = 1.99). Similarly, participants stated to rather like the genre of the game they watched in general (Beat Saber: M = 4.39, SD = 1.65; *Superhot VR*: M = 3.73, SD = 2.17; *Stand Out*: M = 3.30, SD = 2.13).

4 RESULTS

In the first step of our data analysis, we have a look at participants' general motivation to watch videos of VR games. After that, we address our main research question by comparing participants' evaluations of both video perspectives and their preferences.

4.1 Motivation to Watch VR Game Videos

To examine participants' general motivation to watch VR game videos, we analyzed their answers to the uses and gratifications question. Table 1 shows how often participants selected each reason to watch a VR game video. Whereas all different motivations received some votes, the distribution of votes indicates that affective and cognitive gratifications were most prevalent among our participants. The majority of participants would watch videos of VR games, if they seek information about the game (N = 113) or because they enjoy watching them and feel entertained (N = 119). Learning about game strategies was also mentioned often (N = 84). On the other hand, fewer participants see tension release, both in terms of distraction (N = 62) and relaxation (N = 46), as a motivation to watch videos of VR games. Finally, personal and social integrative motives were least prevalent (N = 24 and N = 26).

4.2 Evaluation of First- and Third-Person Perspectives

With regard to our main research question, we analyze how participants perceived both perspectives and which one they preferred.

Overall, the voting shows a recognizable preference for the first-person perspective: 134 of all 217 participants preferred the first-person perspective, whereas only 60 voted for the third-person perspective. Twenty-three participants stated that they have no favorite view. We performed Pearson chi-square tests to investigate if there are significant relations between the preferred perspective and certain characteristics of participants that might influence their vote, namely their gender, whether or not they were familiar with the game that was shown, and their general motivations to watch VR game videos. Regarding gender, vote distribution is very similar between male and female participants, and there is no significant correlation, $\chi^2(2) = 2.31$, $p = .316$. Participants' familiarity with the game seems to have no effect on their voting, either, $\chi^2(2) = 0.35$, $p = .839$. To test the influence of different general motivational aspects, we performed chi-square tests for each of the statements shown in Table 1. The results indicate that whether or not participants selected a particular motivation is not related to their preferred perspective, as no significant correlations could be found (all $p > .348$).

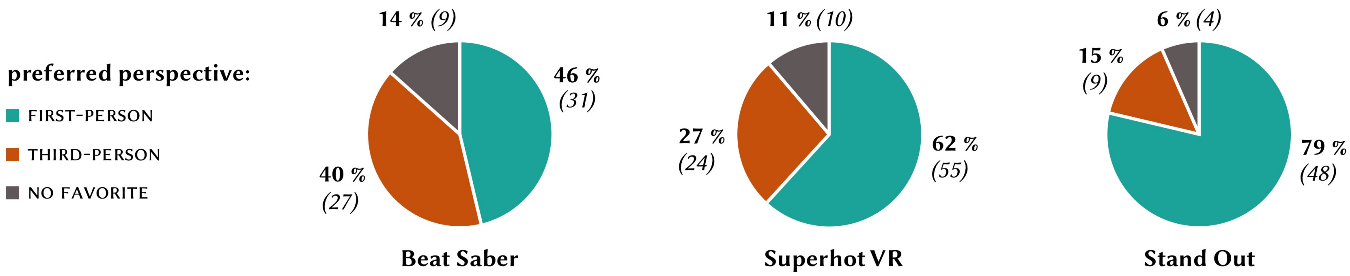

Figure 5: Distribution of the preferred perspective votes of our participants for the three games *Beat Saber, Superhot VR,* and *Stand Out.*

As there might be differences with regard to the three games we tested, we further investigate participants' preferences in the three subgroups for *Beat Saber*, *Superhot VR*, and *Stand Out*. Therefore, we split our data for the following analysis and report results for each game individually. Figure 5 shows participants' preferred perspective in the three study conditions. In line with the overall result, the first-person perspective received most votes in all cases. However, there is a noticeable difference regarding the distribution of votes: whereas there is a clear preference for the first-person perspective in the *Stand Out* group (48 out of 61 participants) and the *Superhot VR* group (55 out of 89 participants), the votes in the *Beat Saber* group are almost evenly distributed with 31 participants preferring the first-person perspective and 27 participants preferring the third-person perspective. A chi-square test underlines that the game that was shown had a significant influence on the vote of the preferred perspective, $\chi^2(4) = 14.48$, $p = .006$, Cramer's $V = 0.183$ (no expected cell frequencies were below 5). Though the effect size is only small ($V < 0.3$), the result indicates that the two video perspectives were perceived differently in *Beat Saber* than in the other games.

To investigate the reasons why participants prefer one view to the other, we compared the viewing experiences between both perspectives and tested for significant differences. Table 2 shows all mean values for both perspectives in the three game conditions. For each game and each dimension of the viewing experience, we performed repeated measures analysis of variance (ANOVA) with perspective as a within-subjects variable and order of game views as a between-subjects factor to test for potential sequence effects. In the following, we report the results of these analyzes for each game. In the interest of better legibility, we only report on sequence effects if they are significant. If not mentioned, the analysis did not show a significant interaction effect between the experience dimension and the order of the two perspectives.

4.2.1 Beat Saber. In the *Beat Saber* group, most differences are not significant. Neither enjoyment nor any ratings of focus and clear view and comprehensibility were rated significantly different between the two perspectives (all $p > .05$). In contrast, the two questions regarding the perceived involvement of the viewers show significant differences: in the first-person view, participants felt more like being part of the game (I1), $F(1, 65) = 6.06$, $p = .016$, and like being in the virtual world (I2), $F(1, 65) = 9.04$, $p = .004$.

4.2.2 Superhot VR. In the *Superhot VR* condition, the repeated measures ANOVA revealed more significant differences. In the first-person perspective, the ratings regarding having a good view of the game world (F3) were higher than in the third-person perspective, $F(1, 87) = 5.64$, $p = .020$. Additionally, the feeling of missing important things (F2) was significantly higher in the third-person perspective, $F(1, 87) = 6.93$, $p = .010$. In terms of comprehensibility, participants had the feeling of significantly better understanding what happened in the game (C1), $F(1, 87) = 7.47$, $p = .008$, and how successful the player was (C3), $F(1, 87) = 7.93$, $p = .006$, in the first-person perspective. Similar to the results in the *Beat Saber* group, both items regarding involvement (I1 and I2) were rated significantly higher in the first-person perspective, $F(1, 87) = 17.19$, $p < .001$ (I1), and $F(1, 87) = 15.91$, $p < .001$ (I2). However, in the *Superhot VR* condition, there was also a significant interaction effect between the ratings for involvement and the order in which the two videos were watched, indicating sequence effects. The rating for being part of the game (I1) was particularly high for the first-person perspective if participants had viewed the third-person perspective video beforehand ($M = 3.64$ compared to $M = 2.88$), $F(1, 87) = 6.27$, $p = .014$. The same pattern becomes apparent for the item *"I saw the virtual world as if I was there myself"* ($M = 3.98$ compared to $M = 2.64$), $F(1, 87) = 13.40$, $p < .001$. All other differences (IMI, F1, and C2) were not significant (all $p > .05$).

4.2.3 Stand Out. In the *Stand Out* group, enjoyment (IMI) was significantly higher in the first-person video, $F(1, 59) = 13.68$, $p < .001$. Moreover, participants gave significantly better ratings regarding focus and clear view in the first-person perspective: they better saw how the player interacted with game objects (F1), $F(1, 59) = 12.47$, $p = .001$, and had a better view of the game world (F3), $F(1, 59) = 15.53$, $p < .001$. At the same time, the feeling of missing important things was lower (F2), $F(1, 59) = 14.43$, $p < .001$. The three items regarding comprehensibility were also rated significantly higher in the first-person perspective: participants better understood what happened in the game (C1), $F(1, 59) = 4.10$, $p = .047$, what the player was doing (C2), $F(1, 59) = 6.98$, $p = .011$, and how successful the player was (C3), $F(1, 59) = 16.60$, $p < .001$. In line with the other two groups, involvement (I1 and I2) was significantly higher in the first-person perspective: $F(1, 59) = 16.39$, $p < .001$ (I1), and $F(1, 59) = 26.23$, $p < .001$ (I2). Summarized, all aspects of the viewing experience

Table 2: Mean values and standard deviations (*M*(*SD*)) of different aspects of the viewing experience in the three study conditions (games) *Beat Saber, Superhot VR,* and *Stand Out,* comparing the first-person and the third-person perspectives. Each item was rated on a 7-point scale ranging from 0 to 6. Significant differences between two perspectives are indicated in bold print.

	Beat Saber (*N*=67)		**Superhot VR** (*N*=89)		**Stand Out** (*N*=61)	
	1st person	3rd person	1st person	3rd person	1st person	3rd person
IMI						
Enjoyment	3.18 (1.47)	3.26 (1.44)	3.03 (1.70)	3.10 (1.64)	**3.21** (1.52)	**2.43** (1.73)
Focus and Clear View						
F1) I saw well how the player interacted with objects in the game world.	4.24 (1.61)	4.57 (1.46)	4.28 (1.60)	4.10 (1.62)	**4.54** (1.21)	**3.74** (1.70)
F2) While watching, I had the feeling of missing important things in the game because I couldn't see them.	2.58 (1.83)	2.19 (1.78)	**2.31** (1.97)	**3.03** (2.07)	**2.70** (1.80)	**3.93** (1.89)
F3) I had a good view of the game world.	4.15 (1.49)	4.24 (1.46)	**4.18** (1.47)	**3.65** (1.72)	**4.14** (1.38)	**3.13** (1.94)
Comprehensibility						
C1) I always understood what happened in the game.	4.52 (1.58)	4.75 (1.47)	**4.33** (1.43)	**3.80** (1.63)	**4.23** (1.33)	**3.64** (1.89)
C2) At any time I could comprehend what the player was doing in the VR world.	3.93 (1.64)	4.42 (1.63)	4.17 (1.51)	4.06 (1.74)	**4.44** (1.35)	**3.78** (1.75)
C3) I was able to understand how successful the player was in the game.	4.33 (1.66)	4.61 (1.59)	**4.37** (1.58)	**3.85** (1.70)	**4.10** (1.47)	**3.16** (1.91)
Involvement						
I1) I felt like being part of the game.	**3.06** (1.88)	**2.46** (1.97)	**3.28** (1.85)	**2.35** (1.95)	**3.67** (1.88)	**2.54** (2.28)
I2) I saw the virtual world as if I was there myself.	**3.54** (1.99)	**2.70** (1.92)	**3.35** (1.85)	**2.44** (1.89)	**3.93** (1.83)	**2.59** (2.03)

differ significantly between the first- and the third-person perspective in the *Stand Out* group, with the first-person perspective being rated better in all cases.

4.3 Thematic Clustering: Reasons for Preferred Perspective

To gain further insight into the positive and negative qualities of the two perspectives, we performed an informal thematic clustering of the free text answers to the question of why participants prefer one perspective to the other. For this purpose, two researchers looked at all answers independently and sorted them by recurring topics. This process was structured into several phases, inspired by the phases of thematic analysis described by Braun and Clarke [3] (though we did not perform a formal thematic analysis): the researchers familiarized themselves with the data, generated initial codes, and derived themes from the codes. After the first round of clustering, both researchers compared their lists of themes and collated codes and discussed all differences. Based on the discussion, a final clustering was agreed upon.

We identified six clusters that describe reasons why participants preferred the first-person perspective, as shown in Table 3. Many participants (N = 38) highlighted a higher involvement perceived in the first-person perspective. They reported that this perspective made them feel like being part of the game or even being the player themselves. Besides, some participants (N = 12) pointed out that the focus was better in the first-person perspective because they were able to see the important things (such as enemies approaching). Participants also reported that the comprehensibility was higher, as they were better able to follow the game events (N = 10). In the third-person perspective, the player was perceived as an obstacle by some participants (N = 10), covering parts of the game and interfering with immersion. Apart from the higher involvement, some participants (N = 8) also emphasized that they prefer the first-person perspective because it is the *"original game perspective"*. This way, they experience how the game looks to the player and can better imagine how it would feel to play the game. Finally, some participants (N = 7) pointed out that the experienced realism was higher in the first-person perspective.

Table 3: Results of the thematic clustering with regard to reasons why participants preferred the first-person perspective. The middle column contains exemplary quotes of participants which were assigned to the topics. The right column shows the number of mentions, i.e. how many single answers of participants were assigned to the respective topic.

Reasons to Prefer the First-Person Perspective	Examples	Mentions
Involvement		
The viewers felt more immersed, they felt like being part of the game, being in the game world, or being the player.	*I like the first-person perspective because it makes me feel like I'm playing the game, not someone else. It is more entertaining when I feel like I'm part of the game.*	38
Focus		
The viewers think that the focus was better, because they were able to see all important things and did not miss something outside the viewport.	*It gives me the ability to see the important parts of the game as they happen, rather than being stuck facing one direction, missing details that are behind my point of view.*	12
Comprehensibility		
The viewers better understood what happened in the game and what the player was doing.	*First person (in this game at least) lets viewers understand what the player is doing.*	10
Obstructive Player in Third Person		
The player in the third-person view was perceived as obstructive, because he obscured the view on the game world and did not fit to the environment.	*First person allows for better visibility without obstruction by the player.*	10
Original Game Perspective		
The first-person view corresponds with the original game perspective, hence viewers can better imagine how it would be to play the game.	*I don't like the mixed reality view. I want to see exactly what the player sees.*	8
Realism		
The experience felt more real to viewers.	*Because it looks more real to me.*	7

For the third-person perspective, we identified four categories of reasons to prefer it to the first-person perspective, as shown in Table 4. The most frequently mentioned reason was that participants ($N = 19$) liked to see the player and his movements. They reported that it was more interesting and entertaining to focus the player and to be able to observe the direct interaction between the player and the game's environment. Related to seeing the player's movement, some participants ($N = 10$) also highlighted that they gained a better understanding of how the game is played and how the interaction works. Hence, they stated that the comprehensibility was better in the third-person perspective. Besides, some participants ($N = 6$) preferred the third-person view, because they experienced some form of motion sickness in the first-person perspective. They reported that it was more comfortable to watch the game in third person. Finally, some participants ($N = 4$) preferred the third-person perspective, because they think that it enabled them to see more of the game world.

Part of the identified reasons to prefer one perspective to the other were mentioned comparably often in all three game groups. More precisely, participants in each group addressed the topics higher involvement, realism, and the original game perspective of the first-person perspective, as well as less motion sickness and a better view on the game world in the third-person perspective. In contrast, some topics were more prevalent for specific games. The better focus and the better comprehensibility of the first-person perspective were predominantly mentioned by participants who had watched the videos of *Superhot VR*: we counted focus eight times and comprehensibility six times in the *Superhot VR* condition, while both topics appeared only two times in each of the other two conditions. However, at this point we want to remind that the *Superhot VR* group was also bigger than the other two groups ($N = 89$ vs. 67 and 61), which might account for such differences.

In the *Stand Out* condition, participants complained more about the obstructive player in the third-person perspective (N = 8) than participants in the other two groups. Moreover, two reasons to prefer the third-person perspective—seeing the player's movements and comprehensibility—were mentioned for both *Beat Saber* and *Superhot VR*, but not for the game *Stand Out*. Even though the Stand Out group was a bit smaller than the other two study groups, the difference is still noticeable.

5 DISCUSSION

We observed an overall preference for the first-person perspective in our study. However, we found significant differences between the three games. This result confirms our assumption that the choice of an appropriate perspective is dependent on the particular game. Moreover, the perceived benefits and shortcomings of both

Table 4: Results of the thematic clustering with regard to reasons why participants preferred the third-person perspective. The middle column contains exemplary quotes of participants which were assigned to the topics. The right column shows the number of mentions, i.e. how many single answers of participants were assigned to the respective topic.

Reasons to Prefer the Third-Person Perspective	Examples	Mentions
Player's Movements		
To see the player's movement and his interaction with the game world is more entertaining and interesting.	*It was more interesting to see how the person was actually moving around and how it looked like he was actually in the game world.*	19
Comprehensibility		
The viewers better understood what the player was doing.	*It was easier to see what the player was doing in the game world.*	11
Motion Sickness in First Person		
It was more comfortable, because in the first-person view viewers experienced dizziness or nausea.	*Watching first person made me kind of dizzy so the third-person perspective was more interesting and more comfortable to watch.*	6
View on Game World		
The viewers feel that they can see more of the game world.	*The third-person perspective gave me a wider view of the world in which the game was taking place.*	4

perspectives as reported by our participants indicate that personal preferences and the motivation of the viewer also play an important role.

5.1 Influence of Game Characteristics on Perspective Preferences

We received the most homogeneous feedback for the game *Stand Out*. Very few participants preferred the third-person perspective, and it also performed significantly worse regarding all measured aspects of the viewing experience, including overall enjoyment. Many participants mentioned a feeling of confusion and the impression of missing essential parts of the gameplay. Whereas viewers of the other two games rather appreciated seeing the player in action according to our thematic clustering, viewers of *Stand Out* experienced the player as obstructive in the third-person view. We assume that this issue is caused by a mismatch between the focus of the viewer in the third-person perspective, which lies on the player, and the location of the important game events: in *Stand Out*, the main actions—such as approaching enemies, the search for coverage or gun fights—are not centered around the player's position, but evolve further away in the surrounding. A first-person perspective better matches this game characteristic and, thus, seems to be more appropriate for this kind of games.

For the game *Superhot VR*, the participants were able to perceive the player's actions and interactions with objects in both views equally and preferences are less clearly distributed. In contrast to *Stand Out*, there is no significant difference in the IMI enjoyment subscale: both perspectives induced similar levels of enjoyment. Since entertainment was the most commonly mentioned motivator to watch VR game videos, we can assume that at least some participants preferred the third-person view in *Superhot VR* for enjoyment reasons. Nevertheless, many participants still disliked the third-person perspective due to the feeling of having a limited view and missing important game events. Comments of some participants point towards a possible explanation: these viewers explicitly stated problems with situations where the player reacted to opponents that were not visible on the screen. This issue seems similar to the problems reported for the third-person perspective in *Stand Out*. Yet, the problem is less prominent in *Superhot VR* and only applies to certain situations. In contrast to *Stand Out*, *Superhot VR* also contains important game events that are directly centered around the player, such as dodging attacks in slow-motion. Such events might account for the fact that still 27% of participants preferred the third-person perspective, which offers a good view on the player. We assume that a more dynamic third-person camera could reduce the issue of the limited view and increase approval of the third-person view to a certain extent.

The most inconclusive results are the ones for the game *Beat Saber*. In this case, our sample shows no clear preference for one perspective. Regarding the spectator experience, only involvement—measuring the feeling of being part of the game—was rated higher for the first-person view. All other subscales, namely enjoyment, comprehensibility, and seeing everything that is important, do not indicate any difference between the two perspectives. These results indicate that the third-person view seems to have advantages to this particular game and that the first-person alternative is not preferable in every case. *Beat Saber* seems to be more appropriate for the third-person perspective than both other games.

Considering the identical study conditions and similar audiences, the reasons for the measured differences between all three games have to reside within the particular game characteristics. Our results indicate that the focus on the player's bodily interaction in the third-person perspective is more compelling for spectators of *Beat Saber* than for viewers of the other two games. In contrast to *Stand Out* and *Superhot VR*, *Beat Saber* requires very fast and coordinated movements of the players. All relevant game events (approaching blocks and hits of the player) are tightly coupled to these movements both temporally and visually. Watching this type of experience is likely more interesting if the viewers can see the players and their movements, as they have an immediate effect on the gameplay. Spectators of the other two games might prefer the first-person perspective, because the player's bodily interaction looks less intriguing and, hence, a clear focus on the in-game events is more interesting.

In addition, the overall high pace of the players' movements in *Beat Saber* makes it hard for new viewers to understand and follow the gameplay. In this case, the third-person perspective could help the audience to gain a better understanding of the game and its goals. For the other two games, it is more important to see the players' view and their interactions with the weaponry to understand the overall gameplay and the players' strategies.

Moreover, we assume that the fixed viewing direction of *Beat Saber* contributes to the success of the third-person view. During the game, the player's view is mostly fixed in one direction, which makes it easy to align the third-person camera with the main course of action. As a result, the viewers' impression of missing essential aspects is reduced. For comparison, *Superhot VR* features a more dynamic environment where enemies approach the player from multiple directions. *Stand Out* provides the most dynamic locomotion system that combines virtual motion and rotation with real movements. Additionally, it relies heavily on long travel distances.

In summary, we assume that the key difference between the three games is the visual coupling of the main game actions and the player's position and movement. In games like *Beat Saber* all relevant game events are centered directly around the player and, thus, emphasized by the third-person-perspective. In games like *Stand Out* most events dynamically evolve in the wider surroundings. In the latter case, the first-person perspective is more appropriate, as it better guides the focus of the spectator towards the important game events.

Despite the discussed reasons that explain the usefulness of the third-person perspective for games like *Beat Saber*, a considerable number of our participants still favored the first-person view for this game. This preference hints towards certain desires of the spectators—such as experiencing the game from the player's view—that require a first-person perspective and are less linked to characteristics of the game. This finding is especially interesting considering that using a mixed-reality third-person view is a widespread approach in current *Beat Saber* videos and streams.

5.2 Subliming the Perceived Strengths and Weaknesses of Both Perspectives

Our analysis of the three VR games has shown that certain game characteristics seem to influence the suitability of the two different streaming perspectives. However, we also consider spectators' personal preferences and motives to be a relevant factor. The UG results revealed two primary motivators of our participants for watching VR game videos: entertainment and information seeking. This finding fits the most frequently mentioned reasons for choosing one perspective over the other: involvement and comprehensibility.

Whereas we could not identify significant correlations between participants' general motives and the perspective they preferred, our thematic clustering of participants' reasons to prefer a certain perspective further helps to understand the perceived strengths and weaknesses of both views. The first-person view is preferred by spectators who want to feel like they are playing the game themselves and who want to see *"through the player's eyes"*. Some participants explicitly mentioned a *"preference for the original perspective"*. An increased involvement was the most prevalent reason of our participants to prefer the first-person perspective. This finding of the thematic clustering is underlined by our questions concerning the feeling of *"being part of the game"*. For all three games, participants felt significantly more as a part of the game in the first-person view. Hence, the first-person perspective better fosters immersive experiences of spectators than the third-person view.

On the downside, some participants indicated that *"seeing through the player's eyes"* made them dizzy and motion sick. In these cases, participants preferred the third-person view, which seems to be less prone to motion sickness.

Interestingly, a better *"comprehensibility"* is mentioned as an perceived advantage for both views. Participants disagreed which perspective provides a better understanding. This feedback might be the result of the different foci of both perspectives: In the first-person perspective, viewers experience the game exactly how it would look like playing it. Hence, some participants might have the feeling that this view provides a better overall impression of the game. In the third-person view, the spectators see the player's movements and the resulting actions in the virtual environment. They might feel that this matching between manipulations and effects provides a better understanding. In this case, the focus does not lie on the original perspective and game events, but on the player and their interaction with the game.

We can summarize the feedback of our participants into three main perceived advantages of the third-person perspective: (1) providing an entertaining experience by showing the player in action, (2) giving a good impression of the VR experience by revealing the player's full-body movement and the relation between the player's manipulations and the effects in the game world, and (3) avoiding motion sickness. Consequently, the mixed-reality third-person approach is particularly promising for games in which the player performs interesting, distinctive movements in real life.

However, the overall preference for the first-person view and the aforementioned concerns demonstrate that the third-person perspective introduces challenges that need to be taken into account. It is essential that the spectator's view is not noticeably limited: spectators must not feel that they miss important events due to a static third-person view or that the player's body might cover significant parts of the environment. Besides the higher immersive experience, these were the most prevalent reasons speaking in favor of the first-person alternative. Hence, the chosen point of view in the third-person perspective must be considered carefully. Especially in the case of dynamic viewing directions, content creators should consider integrating more dynamic solutions, such as aligning the third-person camera with the player's head rotations.

5.3 Limitations and Future Work

Our work presents the first step towards a better understanding of the preferences and experiences of VR game spectators with regard to the streaming perspective. While the study provides valuable insights, there are also some limitations leading to the need for further research.

First of all, we point out that our choice of games does not represent the full VR gaming landscape. Hence, our results are limited to comparable game content. We will consider other genres (e.g., RPGs like *Asgard's Wrath* [37]) in the future to see which features of the two perspectives become particularly prevalent in other scenarios. Furthermore, our study does not take into account other common streaming approaches that integrate the player into the stream in other ways, such as picture-in-picture modes. While this is a limitation of our current work and should be considered in the future, our focus on the comparison of the first-person and the third-person perspectives promotes our understanding of spectator's basic preferences and desires.

Another limitation concerns the concrete implementation of the third-person perspective used in our study, in particular regarding the game *Superhot VR*. As already explained in Section 3.2, the static mixed-reality approach is just one possibility to create a third-person view. Other possibilities include the use of a dynamic camera and the replacement of the real player footage by a virtually created avatar. Some of the perceived shortcomings of the third-person view might trail off when using a different method, in particular a dynamic camera. For instance, the missing focus on current game events or the occlusion of relevant game objects can be reduced by automatically adapting the camera to the player's viewing direction or by enabling spectators to control the viewing angle. While we are convinced that our choice of a static mixed-reality view is appropriate to investigate basic differences between a focus on the game (first-person) and a focus on the player (third-person), future studies with alternative implementations such as using a dynamic camera or a virtual avatar should complement and refine the findings.

Our design decisions regarding the concrete positions of the static third-person viewpoint in the three games (i.e., the position of the spectator's camera) might have influenced the viewing experience, as well. During the design process, we experienced that some positions are better suited than others, though no position seems to be optimal in every game situation, because a static view does not adapt during the course of the game. Hence, we informally tested different positions while implementing the third-person views to find an appropriate position for each game.

Another important constituent of the third-person perspective is the player's persona. We used the same player in all our videos to preserve comparability. Nevertheless, the specific choice introduces possible effects arising from participants' personal preferences regarding gender or appearance of the player. Hence, future studies should include other types of players to investigate potential impacts. Furthermore, preferences may change if the viewers have some kind of relationship with the content producer, for instance, if the player is their favorite streamer. One participant explicitly stated: *"If it's my usual go-to streamer on Twitch, then I would probably like the third-person perspective better because it'd be funnier."*. In such cases, the focus of interest is more on the player and less on the game, which is much better supported by a mixed-reality perspective.

Previous research also indicates that the social interaction between the player and the audience can be an important motivator for spectators to follow game streamers [18, 39]. Particularly in a live streaming context, viewers' social motives become more prevalent, as they have the possibility to interact with the streamer or other viewers while the action takes place. In our study, we presented prerecorded videos and decided to not include social features (i.e., the player did not speak to the audience) to reduce the potential interference effects caused by our specific player. This approach increased the controllability of the study procedure, but limits the direct transferability of our results to live streaming. We assume that the pros and cons of the different perspectives found in our study also apply to live streaming contexts and that our results can also inform live streaming design choices. For instance, streamers using a first-person perspective can further increase comprehensibility by verbally describing which movements they are performing (because these are not visible to the audience).

However, our study does not provide direct indications on how the different perspectives support or interfere with the viewers' need for social interaction. It might become more important to see the player, as visual cues are a central aspect in human communication. On the other hand, a first-person view might provide a closer connection to the player, because this perspective fosters a shared focus and attentional allocation. Future research is needed to test such assumptions. Hence, as a complement to our current work, we recommend the conduct of in-the-wild studies on streaming platforms with actual streamers and their audiences to capture this important social aspect with regard to the preferences of different perspectives. This would also enable a more sophisticated investigation of the correlations between spectators' motives to watch a certain VR game stream and their preferred view.

Another interesting direction for future research in the area of VR spectatorship would be to investigate the experience of spectating VR game streams using HMDs. If the viewer is equipped with an immersive HMD, there are different possibilities to present VR content and the viewing experience will probably differ from 2D displays.

6 CONCLUSION

Delivering the highly immersive experience of VR games to a broad audience via common 2D video streams is a challenge for VR content providers, such as streamers, advertisers, and game developers. This work offers support by giving advice on the choice of an appropriate spectator perspective to foster a positive viewing experience.

Based on our study results, we identified two key factors that need to be considered when deciding between a first-person and a mixed-reality third-person perspective: first, the characteristics of the game, in particular the location of game events in relation to the player's position; and second, the motives and expectations of the audience. While the first-person perspective puts the focus on the game and resembles the player's view, the mixed-reality third-person perspective shifts the focus to the player and the player-game interaction. For games in which most game events evolve directly around the player, the third-person perspective provides viewers with unique insights by revealing the player's real movements and their effects in the game world. This positive effect of the third-person perspective particularly applies to games that require the player to perform interesting, distinctive movements. In contrast, if the main game action is distributed over the game environment and not centered around the player, a first-person perspective is more appropriate due to its immersive quality and a clear focus on relevant game events.

Apart from the game characteristics, content providers also should consider their audience. If spectators are supposed to be mainly interested in gaining an impression of the game and less in the player's persona, the first-person view provides the desired information better than the third-person perspective. On the other hand, if spectators have a keen interest in a specific streamer, their preference might be biased towards a third-person view, which highlights this person.

This work presents the first step towards a comprehensive VR streaming guideline. As discussed above, there are some limitations and follow-up studies with more VR games and different settings are needed to extent our current knowledge. In particular, other implementations of the third-person perspective, for instance with a dynamic camera, need to be investigated to test our hypothesis about the importance of player centricity and visual coupling. Our work paves the way for further research on the spectators' experiences and expectations in the context of VR content. In the long term, understanding how different perspectives contribute to different demands of VR spectators will foster informed design decisions in diverse application areas such as game streaming, VR training and mixed-reality multi-user scenarios.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put…": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	**Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR** *(CHI PLAY '22)*
VR Exergame Design	Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR

Andrey Krekhov, Daniel Preuß, Sebastian Cmentowski, and Jens Krüger. 2020. Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*. ACM, New York, NY, USA, 561–571. DOI: 10.1145/3410404.3414247.

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Figure 1: Our paper contributes a new spectatorship experience for virtual reality games. We blend the player's reflection in the virtual environment and provide a dynamic view frustum that allows viewers to explore the game world by themselves.

ABSTRACT

Watching others play is a key ingredient of digital games and an important aspect of games user research. However, spectatorship is not very popular in virtual reality, as such games strongly rely on one's feelings of presence. In other words, the head-mounted display creates a barrier between the player and the audience. We contribute an alternative watching approach consisting of two major components: a dynamic view frustum that renders the game scene from the current spectator position and a one-way mirror in front of the screen. This mirror, together with our silhouetting algorithm, allows seeing the player's reflection at the correct position in the virtual world. An exploratory survey emphasizes the overall positive experience of the viewers in our setup. In particular, the participants enjoyed their ability to explore the virtual surrounding via physical repositioning and to observe the blended player during object manipulations. Apart from requesting a larger screen, the participants expressed a strong need to interact with the player. Consequently, we suggest utilizing our technology as a foundation for novel playful experiences with the overarching goal to transform the passive spectator into a collocated player.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; • **Software and its engineering → Interactive games**; Virtual worlds software.

KEYWORDS

Virtual Reality; Interactive Frustum; Spectator; Mirror; VR Games; Watching Others Play; Player Reflection

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1 INTRODUCTION

Looking over the player's shoulder has always been a crucial part of our digital gaming experience. There are manifold reasons to watch others play, such as entertainment or learning game strategies [50]. Throughout history, the habit of observing players has evolved from casual get-togethers in domestic settings to highly attended live tournaments with thousands of on-site supporters and even more remote viewers. Not only the competitive scene has evolved: nowadays, many players share their daily gameplay sessions via live streaming platforms like Twitch [2].

In virtual reality (VR), the head-mounted display (HMD) imposes an artificial barrier between viewers and the player, and enjoying the virtual world often remains a lonely experience. Although current technologies allow us to see the virtual world through the player's eyes via local or remote live streaming, the unique selling point of VR—namely the induced presence—remains unavailable to the audience.

What we see at best are the player's movements in the real-world next to a screen with the corresponding first-person view. It remains up to our imagination to merge these two perspectives and to project the player into the virtual environment. Indeed, we can automate this projection by utilizing a green screen setup [34], in which case the audience can see the captured player at the correct virtual position and scale. However, due to the inherent complexity and expensiveness, such setups remain limited to high fidelity video productions required for game teasers and advertising. No less important issue of a green screen is the predefined camera position. If something is happening right outside of the view frustum, the audience will inevitably miss this event.

To summarize, observing someone playing in VR remains an unsolved problem: On one hand, the first-person view fails to convey the full-body interaction, which is a crucial component of player experience in VR. On the other hand, green screen setups, apart from being expensive and requiring lots of effort, work only for a handful of games, such as Beat Saber[4], where we can predict the optimal camera orientation for the whole game session.

This paper contributes to this topic by presenting a novel possibility to watch players in VR. Our interactive approach displays the player in the virtual environment similar to a green screen caption, yet allowing the viewers to control the frustum via physical repositioning (cf. Figure 2). In this way, viewers perceive the visible content as a window into the virtual world rather than a static display—changing position relative to the screen offers different perspectives and prevents missing out on exciting events.

The core idea revolves around the principle of one-sided mirrors. Behind such a mirror, we place a screen that displays the virtual world depending on the observer's point of view. Our silhouetting algorithm renders a dark overlay at the position of the player's reflection to trigger the mirroring property of this local area. As a result, the observer sees the player's mirror image "inside" the virtual world, as shown in Figure 1.

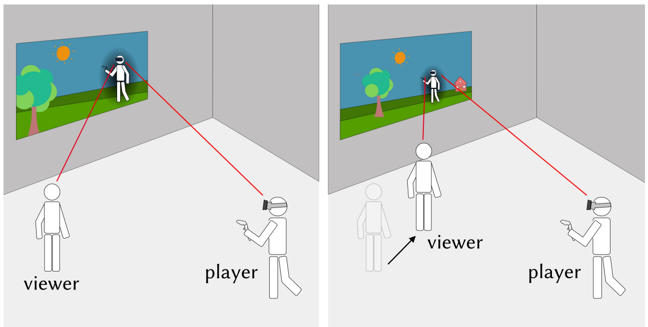

Figure 2: The view frustum is rendered based on the viewer's and player's positions. The viewer, equipped with an HTC Vive Tracker, moves freely in the room to obtain the desired perspective on the virtual environment. In the example above, the viewer moves forward and to the right. This transition increases the field of view, and, e.g., reveals a house in the right corner.

To gather first impressions of this alternative watching experience, we conducted a qualitative evaluation using a VR adventure game as a testbed. The outcomes reveal particular strengths of the idea, such as the overall comprehensibility of the player's actions and the highly appreciated freedom of autonomous exploration. The collected requests of the participants provide a ground for follow-up research and outline possible application areas of our collocated setup.

2 RELATED WORK

Games have always attracted a broad watching audience. In the early days, video games were mostly limited to entertainment machines installed in amusement arcades and surrounded by crowds of interested bystanders [38]. Today, spectating is no longer bound to physical presence. Instead, viewers from all over the world can watch their favorite players using video and streaming platforms, e.g., YouTube [63] or Twitch [2].

Nowadays, spectator is not just a passive onlooker. For instance, the game *Drawful 2* [27] requires the spectators to guess the original phrase based on the player's hand-drawn image. This trend also extends to VR, rendering the virtual experience more social and inclusive. One recent game is *Acron: Attack of the Squirrels!* [23]. The non-VR spectators (or players) act as a team of squirrels and attempt to steal the "Golden Acrons", which are protected by the VR player. In contrast, the two-player version of *Carly and the Reaperman: Escape from the Underworld* [54] requires a close cooperation between the VR player and the non-VR participant in order to overcome the in-game obstacles.

Throughout the years, spectating games has been of ongoing interest to the research community [14, 20, 22, 50, 51]. Especially the recording and streaming of gameplay sessions using online platforms has recently attracted attention due to its importance for the growing esports community [12, 25, 42, 49]. Apart from these distributed approaches using online media, a growing research corpus has focused on the local spectator experience. In this area, the differentiation between active player and passive audience [55] is usually not applicable. Instead, the recent work broadens the definition of spectators to active bystanders interacting with various interfaces [56], often in the form of interactive displays [37, 40, 57].

Common assumptions tend to present gaming as a mostly solitary activity being shared among the active players only. Contrary to this popular belief, social activities, including spectating, are essential components of play [59]. People like to watch others play games for various reasons, such as being entertained, distracted, or learning new game strategies [50]. These desires require a sufficient understanding of the course of action and the players' activities. Reeves et al. [43] classify spectator interfaces based on this information being given to or hidden from the audience. In particular, the authors differentiate between the manipulations conducted by the players and the effects in the game. Based on these two variables, the authors derive four design strategies. For instance, a *secretive* strategy is achieved if both the effects and the manipulations remain hidden. Revealing the effects but hiding the manipulations is more suited for a *magical* interaction. Thus, most gaming activities are better understood and watched with a high information level on both - manipulations and effects.

In contrast to watching, for example, pre-recorded videos, local spectatorship is usually a highly interactive process. Assisting the players is commonly referred to as collocated gaming [17, 29, 60]. The grade of spectator participation can range from entirely passive viewing to actively aiding the players in their task [35]. Downs et al. [19] propose three durable roles: players, audience members, and bystanders. However, the audience is not a static entity and consists of spontaneous and rather ephemeral roles. Such roles include, e.g., commentators, directors, coaches, and cheerleaders.

Another example of viewer interaction is responsive displays. These interfaces can provide unique opportunities for the audience to interact with the game, e.g., by altering their view on the game or assisting the player. In their work, Maurer et al. [35] evaluated how spectators could assist or interfere with the gameplay using gaze tracking.

When using such responsive displays, most users start interacting in a playful manner [58]. Instead of exploring the displayed content, the viewers usually begin to experiment with the available controls and play with their natural gestures. After satisfying their curiosity, they will ultimately shift their focus to the content. This behavior demonstrates the importance of supporting spontaneous and natural interactions as part of the spectator experience. Designing responsive displays in such a user-centric manner can also foster the well-known honeypot effect [62].

All of the previously covered aspects of spectatorship apply to most games in general. However, the particular case of virtual reality (VR) games introduces different and challenging conditions: Players wear head-mounted displays (HMDs) to immerse fully into a virtual world. These devices replace the traditional monitor and hide the gameplay from the potential audience. At the same time, VR games often rely heavily on full-body interactions that are readily observable by bystanders. Therefore, typical VR devices can be classified as "suspenseful" interfaces according to the taxonomy by Reeves et al. [43]: Manipulations are revealed, while effects tend to stay hidden. These characteristics of VR setups do not provide sufficient insights for potential spectators. Another limitation is the social acceptability of HMDs, including AR and VR devices [1, 18, 30]. A spectator might be suspicious of being video-recorded, which results in an underwhelming experience. Therefore, it is crucial to provide the audience with a maximum amount of possible information. Many VR games offer a mirrored view of the players' sight, allowing bystanders to watch the action on a nearby display. However, this perspective does not display the player's full-body actions in the virtual environment, resulting in a loss of information.

Another issue of the HMD-induced barrier is that the player cannot see the audience. Nevertheless, the players are usually still aware that onlookers are watching their full-body movements. This self-consciousness might cause discomfort and induce the feeling of insecurity [45]. On the other hand, such uncomfortable or even embarrassing interactions [36] also have potential benefits. Examples for this are entertainment and sociality, as discussed by Benford et al. [5].

Other approaches provide the spectators with headsets themselves to achieve a shared technological basis. For instance, Larsson et al. [32] evaluate the scenario of recorded VR presentations being watched from the actor's perspective using HMDs. Sra et al. [52] emphasize the importance of equal experiences for all participants in a shared VR space, even if the physical size and shape of the users' individual space is significantly different. In particular, the authors consider three different spatial mapping approaches to allow everyone to perform locomotion based on physical walking [53]. Research on such topics, commonly referred to as collaborative virtual environments (CVE) [6, 7, 15], mostly focuses on distributed [10] or asymmetric [61] spectator experiences for specific purposes, e.g., visualizations [13] or education [41]. In our work, we specifically target the case of non-VR viewers watching VR players.

Instead of moving the observers into the virtual reality, some recent work has blended the elements from the virtual world into the real environment. Zappi et al. [64] used stereoscopic shutter glasses to present interactive virtual objects and real actors on the same stage and achieve a hybrid-reality performance. Jonas et al.'s *RoomAlive* [28] went one step further and turned the whole room into a mixed reality environment shared among players and observers using projector-camera systems. In their work, Hartmann et al. [26] used Kinect cameras to blend the real surrounding into the virtual environment. Similarly, they also integrated a spectator mode projecting the virtual world onto the surrounding walls.

The third type of spectator interface extends the basic approach of showing the players' view on a display. Software solutions such as LIV [34] use green screens and external cameras to blend the real player into a third-person view of the game environment. The result provides a better impression of the players' experience. Gugenheimer et al. [24] take this metaphor one step further. Their *ShareVR* prototype uses a tracked handheld display to achieve a mobile window into the virtual reality that can be moved freely by the spectator. This approach is closely related to our work. With our idea, we replace the handheld device with a very intuitive mirror implementation that also achieves a blending of player and environment.

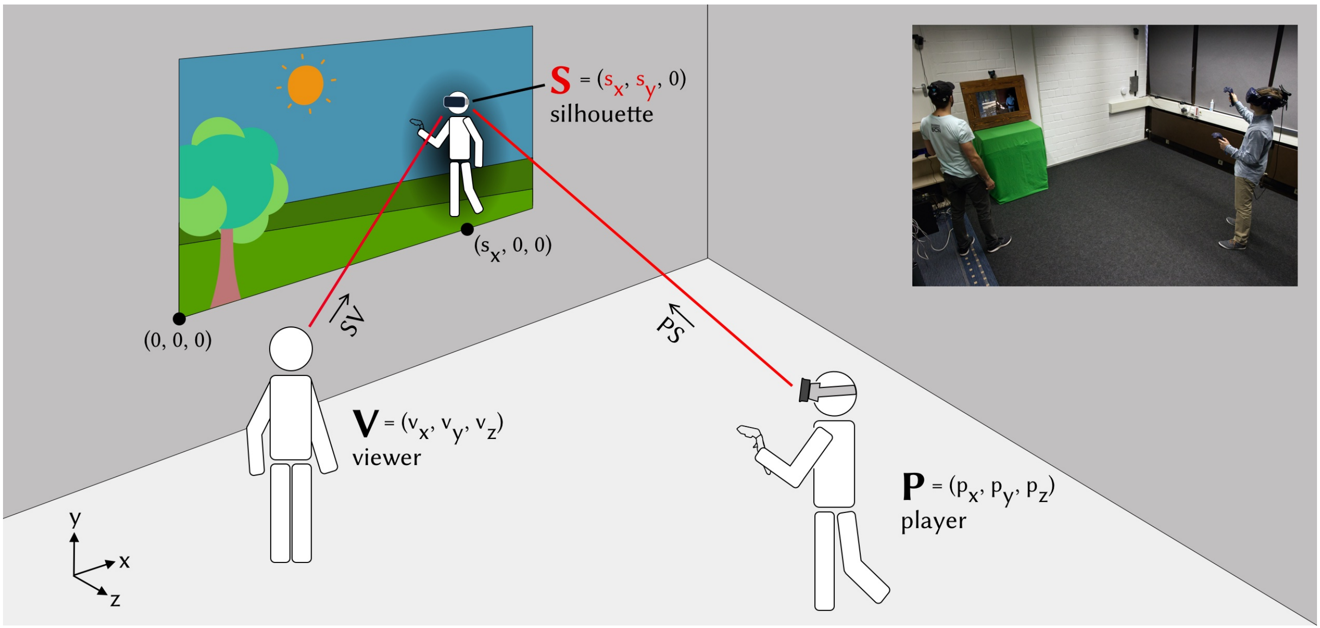

Figure 3: An illustration of the proposed setup. The viewer looks at the screen and sees the player's reflection at the correct position in the game world. To achieve this, we render a silhouette-shaped overlay at this location. The dark silhouette triggers the reflective property of the one-way mirror in front of the screen, blending the player's reflection into VR.

3 THE INTERACTIVE MIRROR EXPERIENCE

VR attracts players with a high degree of immersion that such setups offer. Unfortunately, there is no established way to transfer this feeling of being in the virtual world to the audience—rather than to equip the viewers with a VR HMD, of course [32]. As a result, watching someone playing in VR is not very entertaining. First, we cannot influence what we see, as the view is either predefined (green screen setup) or controlled by the player (first-person view). Second, it is hard for us to set the real-world motions and interactions of the nearby player into the virtual context (first-person view).

This section describes an alternative solution that significantly increases the interactivity on the viewer's side and allows us to see the real player in the virtual world without a green screen capturing setup. By avoiding the impediments mentioned before, our goal is to create a worthy and enjoyable watching experience for VR games.

3.1 Overview

We recommend the readers to inspect Figure 3 to get a first impression of our technique. In short, we rely upon a one-sided mirror in front of a screen to allow the viewer to see both the virtual world and the player's reflection at the correct virtual position. Hence, we can subdivide our approach into two components: an **interactive frustum** for the observer and a **reflection-based visualization** of the player in the virtual world.

The interactive frustum renders the game scene based on the observer's position relative to the screen. Thus, stepping closer or moving to the side allows the viewer to change the perspective and witness a game event that would remain unnoticed otherwise. For instance, by repositioning, the viewer might detect an enemy approaching from the side. The viewer can even inform or warn the player if such an interaction is desired. Hence, the screen is rather deemed a window into the virtual world than a static display.

The concept of reflection-based visualization allows us to display the player's physical body in the virtual environment. More precisely, we see the reflection of the player at the correct position in the game world. Therefore, we place a one-sided mirror in front of the screen. Such semi-transparent mirrors are translucent in case of a bright background, i.e., when the screen shows the game content. However, if the screen is turned off (or black), the installation behaves like an ordinary mirror. Hence, we render a black overlay in the screen area where the observer would see the player's reflection. Seeing this reflection "inside" the virtual world allows us to perceive the player's actions in the gaming context, which gets us closer to this immersive gaming experience.

The provided explanations together make up a top-level view of our approach. In order to become operational, we need to solve the particular problems associated with the described components: First, we need to calculate and render the view frustum depending on the observer's point of view. Second, we have to compute the position and size of the black overlay based on player and observer locations relative to the mirror. The next sections tackle these two challenges and contribute the respective solutions.

3.2 Interactive Frustum

The first crucial part of achieving an interactive, authentic experience is the view-dependent scene rendering on the screen behind the mirror. The viewer must perceive the shown image as a correct reflection of the virtual environment. Just like watching through a real mirror, the frustum is determined by the viewer's perspective and changes depending on the viewer's movements.

Our solution follows the established mirror implementations used in computer graphics literature [21]. However, we do not apply the final texture to an object within the environment. Instead, we render the texture on the display behind the mirror. This difference requires modifications to the usual approach. The complete implementation consists of three consecutive steps:

(1) calculate the mirrored perspective
(2) render to texture
(3) display texture to the screen

In the first step, we calculate the matrices to render a correct image of the reflection. Therefore, we place the scene's camera at the viewer's position. The resulting model-view matrix is multiplied with the mirror's reflection matrix to flip the scene. Next, the camera renders to an intermediate texture. In the final step, we display the texture on the whole screen using a blit operation with the correct texture coordinates calculated from the viewer's position.

3.3 Reflection-Based Visualization

To bend the player's reflection into the virtual world, we render a black overlay at the estimated screen location. Let $S = (s_x, s_y, s_z)$ denote this silhouette, as depicted in Figure 3. We define the coordinate origin to be in the bottom left corner of the mirror, thus setting $s_z = 0$. Note that we can easily enforce this restriction by translating the mirror.

S depends on the player's position $P = (p_x, p_y, p_z)$ and the viewer's position $V = (v_x, v_y, v_z)$. We break this 3D problem down into two 2D cases, as s_x are s_y independent of one another. In the following paragraphs, we derive the solution for s_x, which applies analogously to s_y.

We confine our analysis to the xz-plane with $S = (s_x, s_z)$, $P = (p_x, p_z)$, and $V = (v_x, v_z)$. The normal of the mirror is given by the vector $n = (0, 1)$. By the law of reflection [33], the angles between the incoming vector $\overrightarrow{PS}$ and the outgoing vector $\overrightarrow{SV}$ have to match. By definition of the dot product [44], the following equation holds:

$$\frac{(V-S)}{|V-S|} \cdot n = \frac{(P-S)}{|P-S|} \cdot n. \tag{1}$$

By inserting V, S, P, and n into Equation 1, we obtain:

$$\frac{1}{\sqrt{(v_x - s_x)^2 + {v_z}^2}} \begin{pmatrix} v_x - s_x \\ v_z \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{(p_x - s_x)^2 + {p_z}^2}} \begin{pmatrix} p_x - s_x \\ p_z \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Simplifying the equation above yields

$$\frac{v_z}{\sqrt{(v_x - s_x)^2 + {v_z}^2}} = \frac{p_z}{\sqrt{(p_x - s_x)^2 + {p_z}^2}} \tag{2}$$

We invert and square Equation 2 to obtain

$$\frac{(v_x - s_x)^2 + {v_z}^2}{{v_z}^2} = \frac{(p_x - s_x)^2 + {p_z}^2}{{p_z}^2} \tag{3}$$

Further simplifying Equation 3 yields

$${s_x}^2({p_z}^2 - {v_z}^2) + 2s_x(p_x{v_z}^2 - v_x{p_z}^2) + {v_x}^2{p_z}^2 - {p_x}^2{v_z}^2 = 0 \tag{4}$$

We have to differentiate between two cases. If p_z equals v_z, Equation 4 is simplified to

$$2x(p_x{v_y}^2 - v_x{p_y}^2) + {v_x}^2{p_y}^2 - {p_x}^2{v_y}^2 = 0 \tag{5}$$

We solve Equation 5 for s_x and get

$$s_x = \frac{{p_x}^2{v_z}^2 - {v_x}^2{p_z}^2}{2(p_x{v_z}^2 - v_x{p_z}^2)}$$

If p_z is not equal to v_z, we apply the reduced quadratic formula to Equation 4 and obtain

$$s_{x_{1,2}} = -\frac{p_x v_z^2 - v_x p_z^2}{p_z^2 - v_z^2} \pm \sqrt{\left(\frac{p_x v_z^2 - v_x p_z^2}{p_z^2 - v_z^2}\right)^2 - \frac{v_x^2 p_z^2 - p_x^2 v_z^2}{p_z^2 - v_z^2}}$$

The desired solution s_x is the one between p_x and v_x, i.e., it fulfills the following requirement:

$$min(v_x, p_x) \leq s_x \leq max(v_x, p_x).$$

As mentioned before, we have to repeat this computation for the yz-plane to get the vertical extent of the silhouette. To obtain the top and bottom coordinates of S, we use the HMD position and the location of the player's feet as p_y, respectively.

Furthermore, we have to decide on the overall appearance of the silhouette. The possibilities range from simple blobs to realistic 1:1 silhouettes. We postpone this discussion until Section 4, where we outline the first impressions from such different silhouette representations.

3.4 Hardware Prototype

We manufactured a small-scale prototype to validate our approach and to have a testbed for qualitative evaluation. In a first step, we carpentered a wooden frame to hold the one-sided mirror, as shown in Figure 4. We then disassembled a 24-inch monitor and placed its screen behind the mirror. Such installations are often referred to as "smart mirrors", and detailed assembly instructions can be obtained on DIY platforms such as instructables [3].

To obtain the viewer's position, we mounted a Vive Tracker [16] on the backside of a cap (cf. Figure 1). Depending on particular

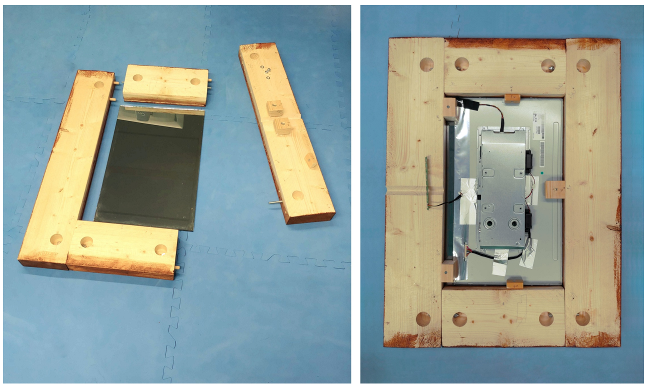

Figure 4: For our prototype, we placed a one-way mirror into a frame and installed a 24-inch display at the back.

requirements, we suggest alternative solutions, such as marker-less single-camera pose estimation [11]. Additionally, we attached a tracker on top of the mirror to obtain its current location. This optional add-in increases the overall portability of our setup, as it allows for repositioning the mirror at any time.

4 EVALUATION

To our knowledge, the proposed approach is the first of its kind. We therefore administered an evaluation to gather first impressions of how potential viewers would perceive such technology. We were particularly interested in the reception of the interactive view frustum, the refection blending, and the overall impression left by our concept.

4.1 Study Procedure

Due to the coronavirus outbreak at the moment of research, we opted for a small-scale qualitative study to gather as many insights as possible from a limited number of participants. The survey took place in a large VR lab at the university to guarantee a sufficient distance between the participant (i.e., the viewer) and the player (i.e., the examiner). After being informed about the study procedure and signing an informed consent, participants completed a questionnaire about their demographic data, gaming habits, and prior VR experiences. Then, the examiner introduced the participants to the operation of our setup (cf. Figure 3).

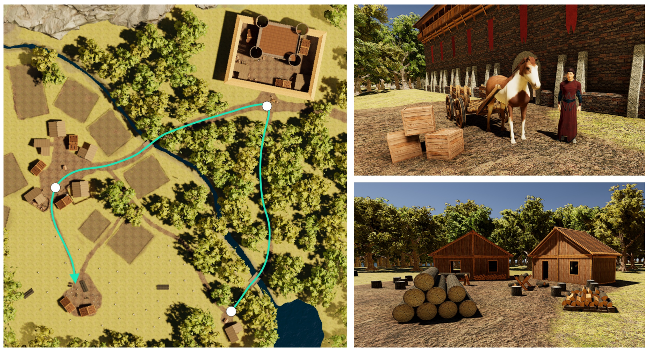

Figure 6: The testbed adventure game. The left image depicts the path taken by the player, i.e., the examiner. Two game quests were interactions, such as sorting crates or collecting wood (right). The two other quests focused on traveling.

Spectating 〉	Questionnaires 〉	Interview 〉	Silhouettes
scripted VR gameplay	IPQ, IMI, custom q's	details, issues, suggestions	diff. shapes/ transparency

Figure 5: An overview of the study procedure.

The remainder of the survey consisted of four phases as outlined in Figure 5: Firstly, the examiner outlined and played the VR testbed game described below. During this gaming session, the participants acted as viewers and could freely move around the room to adjust their view frustum. Secondly, we administered the enjoyment subscale of the Intrinsic Motivation Inventory (IMI) [46] to assess the general enjoyment resulting from our approach, as well as the Igroup Presence Questionnaire (IPQ) [47, 48] to measure the feelings of presence. In particular, we utilized the IPQ subscales spatial presence, involvement, experienced realism, and general presence. We also posed some custom questions (abbreviated as CQ, cf. Table 1) to assess how participants evaluated specific parts of the installation, such as the view frustum and the player reflection. All administered questionnaire items had to be rated on a unipolar scale ranging from 0 to 6 ("completely disagree" to "completely agree"). For IMI, we kept the original 7-point scale. The original IPQ employs a 7-point scale and suggests ratings from -3 to +3. We wanted to keep our questions uniform for the participants and shifted the scale to 0-6. Thirdly, the examiner conducted a semi-structured interview aimed at the identification of particular strengths and weaknesses of our viewing technology. For instance, we asked, "How did you perceive the interactions of the player with the surrounding objects?" (see supplementary material for the complete list of questions). Fourthly and finally, the participants revisited the setup, where the examiner demonstrated our silhouette variations (cf. Figure 7) in a randomized order. We presented these alternatives to determine a possible sweet spot for future applications. In particular, we varied the width and transparency of the blob. Furthermore, we offered a silhouette that mimics the player's arm movements by repeating our silhouetting algorithm for the two tracked controller coordinates. We assessed each silhouette's perception by multiple questions, e.g., "Do you perceive the player as part of the virtual environment?" (cf. supplementary material). In the end, we asked the participants for final comments and debriefed them.

4.1.1 Testbed Game. We used a medieval 3D adventure game designed by Krekhov et al. [31] as our VR scenario (cf. Figure 6). In this game, the player takes up the role of an herbalist's apprentice and solves four different quests. The first and third quest focus on object interaction, i.e., relocating or arranging items. The second and the fourth quest require the exploration of the surrounding via

Figure 7: We demonstrated a variety of silhouettes at the end of the study. From left to right: default oval (used during the gaming session), increased transparency, narrow oval, body-shaped silhouette with tracked arms.

Table 1: Mean scores (range 0-6) and standard deviations of the custom questions (CQ).

CQ1	I understood what the player was doing in VR at any point during operation.	5.11 (0.78)
CQ2	I could see well how the player interacted with the in-game objects.	5.33 (0.71)
CQ3	I did not feel like I missed any essential game events.	3.78 (1.64)
CQ4	I was able to control my perspective on the game world freely.	4.11 (1.27)
CQ5	I could not see everything I wanted in the game world.	4.56 (1.59)
CQ6	I was in the same world as the player.	4.00 (1.12)
CQ7	I saw the virtual world as if I was there.	2.67 (0.87)
CQ8	I enjoyed my ability to explore the virtual world via repositioning and head movements.	5.56 (0.53)
CQ9	It was fascinating to see the virtual world through the mirror.	5.22 (0.44)
CQ10	I would have liked to interact with the player.	4.67 (1.66)
CQ11	I was part of the game.	2.22 (1.20)
CQ12	I felt passive throughout the gaming session.	5.00 (1.32)
CQ13	I would have preferred a larger screen.	5.78 (0.44)
CQ14	The view frustum was too small for me.	5.22 (0.83)

point and teleport locomotion [8]. Hence, the participants experienced local, player-oriented interactions as well as long-distance travel in an open world.

The overall duration of the gaming session was approximately 15 minutes. To guarantee similar conditions for all participants, we scripted the examiner's gameplay. We neither restricted nor encouraged the communication between the participants and the examiner. However, the examiner was advised to ignore major requests (e.g., going to a different location) to prevent significant alterations in experienced gameplay.

4.2 Results and Discussion

Because of the pandemic situation, we limited the number of participants to nine persons (three female, six male) with a mean age of 27.8 years (*SD* = 7.66). Four of them were students, and the others were employees. All participants reported playing digital games regularly, and eight of them had prior experiences with VR HMDs. An excerpt of our custom questions is outlined in Table 1, and the outcomes of the IMI and the IPQ questionnaires can be found in Table 2. To evaluate IMI, we followed the respective guidelines [46], i.e., we first computed the mean of all seven items for each participant and used this data for further computations.

The interviews and the discussion on the silhouette shapes were audio-recorded with the permission of the participants. We applied the six-phase process of reflexive thematic analysis by Braun et al. [9] to analyze the interview data, following a deductive approach. As a result, we identified themes such as "player locomotion" or "reflection/visibility." In the following, we group all obtained results and insights into respective thematic areas.

4.2.1 Overall Concept. The first questions of our semi-structured interview targeted at the overall impression left by our setup. Seven participants explicitly told us that they were positively surprised of the overall experience, as they *"didn't think that it might be possible to exploit reflections in such a way"* ***(P4)*** and described it as an *"unusual but refreshing solution"* ***(P7)***. The high values for CQ8 (*M* = 5.56, *SD* = 0.53) and CQ9 (*M* = 5.22, *SD* = 0.44) expose the overall excitement of the participants regarding the possibility to control their view frustum via repositioning. One participant was particularly impressed by the performance: *"I expected some lags and delays when I heard about the dynamic viewport. But then, it was smooth, without flicker or lag, even during fast head movements"* ***(P4)***.

This positive overall impression is supported by the high values of the IMI enjoyment/interest subscale (*M* = 4.51, *SD* = 0.53). This outcome is even more conclusive under the circumstance that the participants did not play the game themselves and were only in an observer role. This initial appreciation could be due to the innovative character of our setup. We suppose that this novelty effect might wear off after a while. Nevertheless, the gathered insights support our claim that the proposed technique leads to an enjoyable experience and is worth further explorations.

4.2.2 Perception of the Player's Reflection. Our motivation behind the reflection utilization was to allow the viewer to see the player inside the virtual world. We suggest that such a third-person view

Table 2: Mean scores (range 0-6) and standard deviations of the IMI and IPQ subscales.

IMI	Enjoyment/Interest	4.51 (0.53)
IPQ	General	3.22 (1.20)
	Spatial presence	3.56 (0.92)
	Involvement	2.94 (1.29)
	Experienced Realism	2.53 (0.48)

enhances the comprehensibility of player's actions due to the additional context provided to the audience [43]. This assumption is supported by the high values for CQ1 (M = 5.11, SD = 0.78) and CQ2 (M = 5.33, SD = 0.71). These outcomes are in line with the insights from our interviews, where participants reported to *"understand what he [the examiner] was doing with the objects in front of him"* ***(P1)***. The participants also mentioned that *"especially the moments when the player engaged with an NPC were most interesting to watch"* ***(P8)***. Overall, the interaction aspect was perceived as very immersive: *"when he [the examiner] threw a crate, or the scroll it felt like these objects will fly at me"* ***(P5)***.

However, the fact that the viewer can see both the real player and the reflection is also a potential source of confusion. For example, one participant stated that *"in situations where the player physically approached me from behind, I had a strong need to turn around"* ***(P1)***. Another participant, in contrast, *"did not perceive the real player anymore and only looked at the VR mirror"* ***(P3)***. Also, some participants pointed out the depth ordering issue, as our silhouette computation is currently limited to the screen space: *"sometimes it was hard to say whether an item was in front or behind the player, particularly when it was covered by the dark blob"* ***(P6)***. To fix the depth order, we need to include the depth coordinate s_z in our future implementation in the same computational way as we did with s_x and s_y.

4.2.3 Shape of the Silhouette. We can not derive a general trend regarding the optimal appearance of the silhouette, as we received controversial opinions on this topic. What we can say is that the complex silhouette that included the player's arms was disliked by all participants. The reasons were manifold, e.g., four participants complained that *"the dark arm notches were too distractive and occluded too much"* ***(P2)***. Even worse, two participants *"could not see the reflected arms properly within the dark area"* ***(P7)***. One participant rated this silhouette as *"unrealistic, resembling more this skydancer or tube man thing"* ***(P1)***.

Similarly, there was no common agreement regarding the width of the silhouette. One participant strongly disliked the narrow representation because *"it was hard to see the player"* ***(P3)***. Otherwise, participants did not express any tendency toward the wider or more narrow shape. Regarding transparency, only one participant preferred a highly transparent or no silhouette at all. Six of the remaining participants requested a transparency level depending on the virtual surrounding, asking us to *"make the silhouette darker when the player is in a bright and feature-rich environment"* ***(P9)***. In contrast, dark areas barely require a silhouette to see the player's reflection.

4.2.4 Immersiveness of the Interactive Frustum. We designed the dynamic frustum to lower the HMD-induced barrier between the player and the viewer. CQ6 (M = 4.00, SD = 1.12) supports our assumption, as participants felt like they are in the same world as the player. We argue that this world is the physical realm and not the virtual surrounding, as indicated by the low values for CQ7 (M = 2.67, SD = 0.87). In other words, the frustum brings the player into the living room, rather than the viewer into the virtual environment. This explanation also aligns with the values for the general (M = 3.22, SD = 1.20) and the spatial presence (M = 3.56, SD = 0.92) subscales of the IPQ.

As indicated by CQ4 (M = 4.11, SD = 1.27), the participants had no trouble to control the view frustum according to their wishes and enjoyed such a possibility to explore the virtual world (CQ8; M = 5.56, SD = 0.53). Three participants explicitly described the experience as *"if I would look out of a window and see the game world"* ***(P8)***. More importantly, they barely missed out on any important events (CQ3; M = 3.78, SD = 1.27). However, the additional degree of freedom provided by the frustum is hindering during player locomotion. Seven participants mentioned a loss of orientation during the teleportation procedure. The point and click teleport was described as *"instant and unpredictable jump that I could not control and needed a while to find some reference points in the scene to know where we [the participant and the examiner] arrived"* ***(P2)***. Two participants disclosed that they *"tried to reposition the view such that the teleport target and the player are both visible"* ***(P5)***. Hence, we assume that our setup has a notable drawback for games that involve a large amount of player relocations, as the viewers need a certain amount of time to reorient themselves in the virtual world.

4.2.5 Limited Screen/Mirror Size. The major point of criticism was the size of the view frustum. Nearly all participants requested a bigger screen/mirror (CQ13; M = 5.78, SD = 0.44) and remarked that the viewport was too limited (CQ14; M = 5.22, SD = 0.83). Accordingly, the participants could not see everything that they wanted to see (CQ5; M = 4.56, SD = 1.59). Three participants told us that *"sometimes, it was hard to find a proper angle that would reveal the player and the area of interest in the game world"* ***(P2)***. Similarly, one participant explained: *"it looks best when the player entirely fits into the screen from head to foot, but this is hardly possible because of the small screen size"* ***(P9)***. This screen size issue was also reflected in the viewers' behavior during the gaming session—most viewers stood close to the mirror, which results in a smaller player silhouette and an increased field of view. Thus, we must conclude that a 24-inch screen is definitively too small and suggest to utilize a minimum of 50 inches in the future.

4.2.6 Missing Interaction with the Player. The lowered barrier between the player and the viewer, combined with the feeling of being in the same world, naturally evokes a need for interactivity. Hence, we postulate that our setup is especially interesting for collocated gaming purposes [17, 29, 60]. As indicated by CQ11 (M = 2.22, SD = 1.20), the participants did not perceive themselves as a part of the game and felt rather passive (CQ12; M = 5.00, SD = 1.32). Instead, they would have liked to interact with the player (CQ10; M = 4.67, SD = 1.66).

We see this input as an important aspect of future research, as our installation could lead to novel playful experiences that transform the viewer from a passive spectator [19] to an equal co-player. For instance, one participant proposed to *"include game objects that are visible only for the observer"* ***(P4)*** or to *"turn the watcher into an early warning system for enemies sneaking up from behind"* ***(P4)***. Such an asymmetric information distribution would upgrade the spectators from "witnesses" of the story to actors or even "heroes" [39]. Another participant mentioned mixed reality sports games as a possible application area: *"it could be fun to play some sort of tennis, me in front of the mirror and my opponent in VR"* ***(P2)***. For this purpose, one could blend the real surrounding into

VR, as proposed by Hartmann et al. [26], or even turn the room into a shared mixed reality environment, as done by Jonas et al. [28].

5 LIMITATIONS

The outlined setup is the first of its kind. Hence, the method and its evaluation come with weaknesses and limitations that have to be discussed explicitly. This section is dedicated to a critical, retrospective assessment of the presented work, as we aim at providing a comprehensive overview of the pros and cons of our system and paving the way for meaningful future work in this direction.

5.1 Limitations of the Study

Due to the restrictions caused by the pandemic, we had to limit our evaluations to a bare minimum. Having only nine participants limits the conclusiveness of the gathered results. For instance, this small sample does not allow us to draw general assumptions on the optimal silhouette shape—instead, we consider such outcomes as preliminary insights. Another issue is that eight out of nine participants were already familiar with HMDs, which induces an initial bias. For instance, inexperienced participants might rate the spectatorship role less engaging, as they would be more interested in a first-hand VR experience.

Furthermore, the study procedure consisted of multiple steps (cf. Figure 5), and each participant underwent multiple evaluation rounds, e.g., observing the gameplay, participating in an interview, and returning to the game to rate various silhouettes. This complexity could have caused fatigue and bias: for instance, seeing the complete gameplay with one specific silhouette shape could have impacted the final assessment of such shapes.

Our evaluation was limited to an explorative survey and aimed at gathering first impressions left by the technique. Hence, at this moment, we cannot provide meaningful comparisons to other spectatorship techniques. This is an important limitation and needs to be addressed in a follow-up quantitative study after the pandemic. In particular, there is a need for a baseline comparison between our mirror, a default first-person perspective, and different third-person solutions (see future work section).

Another restriction of our study is the utilization of only one testbed game. As we have seen in our case, the appreciation of the technique depends on the game events. Teleportation and long-distance navigation caused disorientation, rendering such events rather unattractive for spectators. In contrast, local interactions, e.g., picking up or moving objects, were perceived as engaging and immersive. Hence, we have to consider a diverse set of games before drawing overarching conclusions on our technique's general applicability.

Regarding the applied measures, two shortcomings have to be mentioned. Firstly, we did not instruct the participants regarding the interaction and communication with the player. Thus, despite the outcomes of CQ10, there were no interaction attempts. We argue that this behavior is due to the formal study atmosphere, amplified by the pandemic influence. Secondly, we focused solely on the viewer's experience and ignored the player in our setup. However, to become established, the technique needs to provide an adequate player experience as well. For instance, the colocated spectator could cause discomfort of the players, as, e.g., outlined by Rogers et al. [45].

5.2 Restrictions of the One-Way Mirror Setup

The initial implementation of the one-way mirror idea comes with inherent strengths and weaknesses and should not be considered an all-round solution. In our version, the interactive frustum is computed based on the viewer's position. Hence, such a setup is currently limited to one observer—an issue for, e.g., public spaces with multiple interested persons.

Furthermore, the technique requires certain modifications to the game (engine) to render two perspectives—one for the player and one for the observer. This overhead also implies increased hardware requirements. We point out that the observer's perspective does not require the same high refresh rates as the VR version. A further hardware-related restriction is a need for additional components, i.e., a one-way mirror and two default HTC Vive Trackers, limiting the out-of-the-box applicability of the method.

Another critical design consideration is the visualization of the player. In our case, we used the player's reflection. Like a green screen or *RoomAlive* [28], the viewer sees the real player, which fits less well into the virtual environment compared to an avatar. This break in the appeal can lead to a decrease in perceived presence. On the other hand, only a few VR games provide a player model. Although some green screen solutions, such as LIV [34], provide fallback models, we argue that an inappropriate choice of the avatar can hamper the immersion even further. Besides, we suggest that seeing the real player could enhance the bond between player and viewer and provide a refreshing experience compared to default avatars.

6 FUTURE WORK

The mentioned limitations provide an outline for further research on the one-way mirror idea. In a first step, we suggest an in-depth, quantitative evaluation of our technique to understand how it performs versus established solutions. We plan to conduct a baseline comparison to the following candidates:

(1) first-person perspective: the viewer sees the player's perspective; i.e., the default spectator scenario
(2) third-person perspective (player): a green screen is used to inject the player into the virtual environment
(3) third-person perspective (avatar): again, we capture the player's movements, but the player is replaced by an avatar in-game

Depending on the outcomes of (2) and (3), one might also consider adding an avatar mode to our technique. Therefore we have to disable the dark silhouette and render the avatar at the respective position. Furthermore, we suggest assessing the player experience in our setup. We hypothesize a slight discomfort [5, 45] caused by the invisible, yet colocated spectator. In this case, our technique could benefit from a minimalistic visualization of the viewer from the player's perspective.

One possible follow-up of our setup is its adaptation to a distributed scenario. This is especially viable in the times of the coronavirus pandemic, as it supports social distancing. A remote session in our case would even allow multiple spectators, each equipped with an individual, dynamic view frustum, e.g., a tablet. Note that this variation requires a video capturing device on the player's side, as we cannot rely on the direct reflection anymore.

Our evaluation results suggest that the display size needs to be extended in future hardware iterations. The small screen forced the viewers to stand very close to it, which restricts mobility and limits the idea's overall potential. Another point that can be improved is a more sophisticated attenuation of player teleportation. In our study, the viewers experienced a loss of orientation during fast travel, which could be reduced by supporting VFX/SFX effects that signal upcoming teleportation.

Finally, our study participants expressed a strong need to interact with the player, be it verbally or playfully. We gathered some preliminary suggestions, including sports games and games with asymmetric information distribution. We suggest implementing such testbed scenarios to increase the viability of the presented setup. Ultimately, such games will pave the way to more inclusive, engaging, and active spectatorship experiences.

7 CONCLUSION

Our work presented a novel possibility to watch players in VR. Instead of looking at a static display, the spectator can change the point of view by repositioning and changing the viewing angle. This approach turns a common screen into a view-dependent window, thus significantly increasing the autonomy of the viewer. The setup is completed by a one-way mirror in front of the display. Together with our silhouetting algorithm, this mirror allows the spectator to see the player's reflection at the correct position in the game world, blending the player into the virtual environment. The result is similar to a green screen caption, yet without the capturing overhead and, most importantly, with a spectator-controlled viewport.

Our exploratory study underpins the overall positive appreciation of our technique. The reflection-based player visualization renders object and NPC interactions comprehensible and engaging. The dynamic view frustum enables autonomous exploration of the surroundings and prevents viewers from missing out on interesting game events. Taken together, these two components of our system lower the HMD-induced barrier between viewers and players, evoking the feeling of being in the same world. Hence, our collocated setup provides a solid foundation for novel playful experiences that transform a passive spectator into an engaged, mixed-reality co-player.

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Locomotion

Virtual Body Scaling	GulliVR: A Walking-Oriented Technique for Navigation in Virtual Reality Games Based on Virtual Body Resizing *(CHI PLAY '18)* Outstanding: A Multi-Perspective Travel Approach for Virtual Reality Games *(CHI '19 late breaking, CHI Play '19)*
Scaled Walking	Outpace Reality: A Novel Augmented-Walking Technique for Virtual Reality Games *(CHI PLAY '22)*
Gesture-Based Navigation	Tug & Swing: Combining Point-Tugging and Arm-Swinging for Comfortable and Efficient VR Locomotion *(CHI '23 - under review)*

Interaction

Movement Behavior	Effects of Task Type and Wall Appearance on Collision Behavior in Virtual Environments *(IEEE CoG '21)*
Gait-Related Interactions	Towards Sneaking as a Playful Input Modality for Virtual Environments *(IEEE VR '21)*
Inventories for VR Games	"I Packed My Bag and in It I Put…": A Taxonomy of Inventory Systems for Virtual Reality Games *(CHI PLAY '19 work in progress, IEEE CoG '21)*

Perspectives

Animal Body-Ownership	The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games *(CHI PLAY '18 work in progress, IEEE CoG '19)*
Animal Avatars in VR Games	Beyond Human: Animals as an Escape from Stereotype Avatars in Virtual Reality Games *(CHI PLAY '19)*
Character Transitions in VR	"It's a Matter of Perspective": Designing Immersive Character Transitions for VR Games *(CHI '23 - under review)*

Applications

Streaming VR Content	Streaming VR Games to the Broad Audience: A Comparison of the First-Person and Third-Person Perspectives *(CHI '21)*
Local VR Spectatorship	Silhouette Games: An Interactive One-Way Mirror Approach to Watching Players in VR *(CHI PLAY '22)*
VR Exergame Design	**Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame** *(CHI PLAY '21 work in progress, CHI '23 - under review)*

Exploring the Potential of Vertical Jump Training in Virtual Reality

Sebastian Cmentowski and Jens Krüger. 2021. Exploring the Potential of Vertical Jump Training in Virtual Reality. In *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '21)*. ACM, Virtual Event, Austria, 179–185. DOI: 10.1145/3450337.3483503.

Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame

Sebastian Cmentowski, Sukran Karaosmanoglu, Lennart E. Nacke, Frank Steinicke, and Jens Krüger. 2023. Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame. In *Submission to the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)* (under review).

Exploring the Potential of Vertical Jump Training in Virtual Reality

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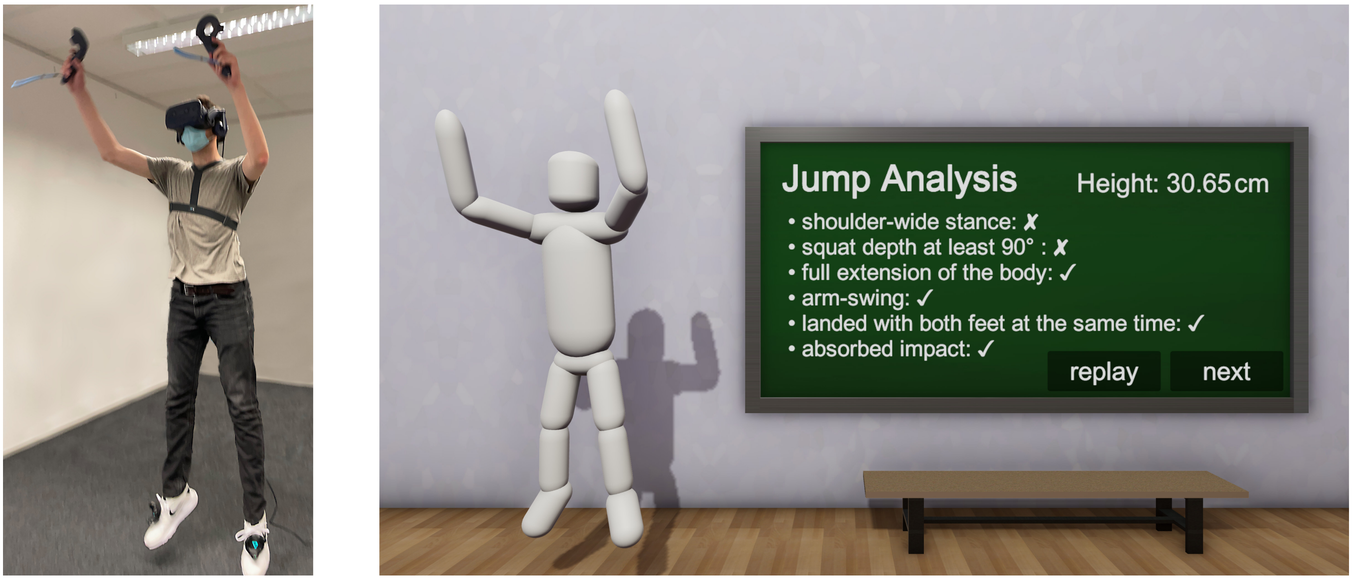

Figure 1: Left: Participant performing a vertical jump with trackers and HMD. Right: Visualization and analysis of the recorded jump.

ABSTRACT

In many athletic activities, jumping is a fundamental skill requiring strength, stability, and coordination. It is also a good indicator for general fitness and can predict the individual risk of injury. Therefore, most people profit from training to improve their jumping performance. However, amateur athletes might not have access to professional analysis equipment or jump trainers, and unsupervised training, such as online videos, cannot provide individual feedback. Therefore, we explore the potential of using virtual reality as a widely available platform for a personalized jump training application. Based on the current state of research, we discuss and identify possible use cases, such as instant replays of recorded jumps, an individual motion analysis, automatic exercise recommendations, and gamified workouts. We also demonstrate the feasibility of jumping interaction in virtual scenarios with an early prototype and explain future research directions.

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CCS CONCEPTS

• **Applied computing → Interactive learning environments**; • **Human-centered computing → Virtual reality**; • **Software and its engineering** → *Interactive games.*

KEYWORDS

virtual reality; vertical jump; training; learning; sport; exergame

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1 INTRODUCTION

Similar to walking or running, jumping is a fundamental human skill learned at an early age and improved throughout our lives. Apart from apparent applications in jumping-intense sports, such as basketball [27] or volleyball [65], the vertical jump is also an excellent indicator of general fitness levels [34], neuromuscular coordination [54], and muscle composition [13]. Improved vertical jump performance directly contributes to various athletic activities, such as football [15], weightlifting [32], or swimming [3]. Furthermore, jumping is used in rehabilitation and diagnosis to measure changes in pathology [36, 37]. Analyzing individual jumping performance is also used to identify and treat muscular or coordinational weaknesses known to predict increased risks for common sports-related injuries [21].

Even though humans learn to jump implicitly while growing up, it remains a *"complex polyarticular dynamic movement requiring intermuscular coordination"* [62]. Specific training can therefore help to improve individual execution, prevent injuries, and boost performance [6, 72]. However, performance evaluation and movement analysis are not trivial tasks for such a multisegmental explosive movement that involves all parts of the human body and takes less than four seconds to execute [72]. Experienced jumpers initiate extension of the different joints, i.e., knees, hips, and feet, with a delay of less than 25 milliseconds [41], making it extremely challenging to identify individual weaknesses or asymmetries within the compound movement. Therefore, professional athletes and researchers typically rely on motion-capturing systems for precise analyses [4, 6, 51]. However, in the recreational sector, such setups are usually not readily available.

Additionally, sports that do not rely on jumping as a primary exercise often do not incorporate jump training into the routines. Feedback from our participatory design phase suggests that even in basketball training, such dedicated exercises might not receive the necessary attention. As an alternative for individuals aiming to work on their vertical jump performance to improve lower body strength, stability, and coordination, an extensive collection of online guidelines and videos offers unsupervised exercises [2, 56, 60]. However, such general routines cannot correct individual mistakes or account for personal weaknesses. Despite these disadvantages, the popularity of unsupervised training is constantly growing and has received another big boost during the COVID-19 pandemic [68].

One platform that still has a limited but quickly growing share in training and exercise applications is virtual reality (VR). The latest promising increases in sold headsets have been mostly attributed to cheaper portable devices and individual popular workout games, such as *BeatSaber* [7]. Although these titles, which allow players to spice up their cardio workouts in a gamified virtual surrounding, are among the most popular applications, they do not max out the possibilities of VR-based training. The latest research exploring novel experiences, such as the feeling of vertigo [17], gait-related interactions [24], or collocated gaming [76], demonstrate this untapped potential. Further, studies on VR-based training have demonstrated that virtual experiences can lead to transferable improvements in table tennis, baseball, or dart skills [57]. However, most of these projects have focused on individual technical- or tactical-intensive activities and avoided highly physically demanding movements like the maximal vertical jump.

Considering the additional challenges when performing fast and abrupt full-body movements in a virtual environment, past research, not surprisingly, concentrated on alternative concepts such as practicing tennis volleys in slow-motion [45]. The first and most significant point of concern about performing vertical jumps with a heavy head-mounted display (HMD) covering the view is the subject's safety. Is the headset's strap sturdy enough to secure a proper fit during a jump? Even if the headset stays on the head, it might still slightly slip, causing blurry vision or tracking errors that could lead to potentially dangerous situations. Apart from these technical issues, users might also feel insecure and thus refrain from performing a jump with maximal force. Finally, most current VR systems support tracking of body parts, controllers, or dedicated devices, such as Vive Trackers [40]. Although these capabilities are highly beneficial in tracking and analyzing the user's jumping skill, it remains unclear if tracking precision and frequency suffice.

Despite these open questions and technical problems, the potential of VR-based vertical jump training remains promising. The unique capabilities of VR setups could address many of the challenges mentioned earlier and provide a personalized and analytical training experience. As explained, the correct execution of vertical jumps is usually hard to evaluate. Tracking the jump with a VR setup can provide essential information, such as the jump height or movement of individual joints. This data would be instantaneously available to the user, e.g., in the form of a slow-motion replay, progress tracking over multiple jumps, an individual motion analysis, or resulting automatic training recommendations based on the user's performance. Further, jump training often involves a significant amount of plyometrics, such as drop jumps or countermovement jumps [62]. These exercises might be directly integrated into the virtual experience. Employing a gamified approach could motivate users to perform the repetitive training jumps maximally, as research has shown that submaximal jumps train different muscle groups and might not lead to the desired results›[51]. Finally, introducing jumping activities in VR might spark a range of new bodily experiences and exergames beyond training.

In this work-in-progress paper, we introduce this highly complex topic by providing an overview of the relevant research background, sharing our ideas and concepts, and presenting a first prototype towards an unsupervised immersive training experience for the vertical jump. In particular, this paper consists of three parts:

(1) We summarize the related work on VR-based training, jumping-related biomechanical basics, and training modalities for the vertical jump. We use these insights to discuss possible applications for VR-based training.
(2) We present our participatory design work on an early prototype. Therefore, we address the safety, comfort, and tracking challenges. Further, we present a first feedback system, including instant replay and postural feedback.
(3) In the last part of this paper, we elaborate on our next steps towards a fully implemented training application and our plans for a comparative study.

2 TRAINING THE VERTICAL JUMP IN VIRTUAL REALITY

Training is one of the most common applications of VR systems [18]. Especially in situations where real training is difficult or dangerous [44], VR provides a simple alternative to assess the individual performance [71], create an active learning experience [8], and enhance motivation [28]. In sports, VR has already been applied to a variety of use cases. Various studies have employed the advantages of virtual scenarios to analyze athletic performance [9, 25], understand motor and perceptional skills [22, 26], or train movements and tactical behavior [35]. VR setups have been also used for rehabilitation and therapy [23, 59]. Regarding sports training in VR, most research has relied on either static equipment, like rowing machines [67], or focused on hand-eye-coordinational skills, such as table tennis [58] or darts [69]. Based on this current state of research, we explore the potential use cases of VR-based jump training by considering training modalities and biomechanical principles. Therefore, we discuss the different training phases, starting with performance measures and movement visualizations, before covering exercise recommendations and user motivation.

2.1 Progress and Performance Measures

Vertical jump performance is a widely established measure of functional performance. Therefore, the progress of strength training, in general, and jumping exercise, in particular, is usually monitored through vertical jump tests [46]. Such tests aim to precisely calculate the personal jump height while being robust against sources of interference. The most accessible approach is the jump & reach test: Athletes mark the highest reachable points while standing and jumping on a wall to calculate their jumping power as the difference between both points [43]. Even though special devices have been developed to ease test execution [50], this approach has several disadvantages, such as dividing the athlete's attention between jumping and marking the highest point. Therefore, this test was mostly replaced by force platforms [14]. These devices calculate the jump height by measuring the airtime between take-off and landing. In contrast to jump & reach tests, no specific user behavior is necessary. However, athletes may distort the resulting values by flexing their knees prior to landing to delay ground contact [46].

Considering this state of the art regarding vertical jump tests, VR setups offer great potential for measuring individual jump performance. First, three-dimensional (3D) user tracking within the play area provides a straightforward and reliable foundation for jump height calculation. Vanezis and Lees [72] argue that the vertical jump is best measured as the displacement of the athlete's center of mass (CM), which is easily achievable by attaching a dedicated tracker to the user's chest. Alternatively, it might suffice to record the headset's movements as deviations between head and trunk are minimal. Measuring the vertical movement of the body guarantees precise and reproducible tests and allows users to track their progress reliably throughout the training period. Further, extending performance measurement beyond the pure height calculation is easy. Attaching dedicated hardware trackers to hands, feet, knees, and torso provides a more holistic impression of the user's movements. This information can be used for detailed performance measures, such as posture and movement quality, asymmetries between body sides, or single joint moments.

2.2 Visualization

Even though research has indicated that most people perform vertical jumps according to a similar and robust stereotypical pattern [12], the individual execution still differs from athlete to athlete [72]. For instance, some people emphasize knees over hips and vice versa. These particularities are not necessarily detrimental to the overall performance, but some universal guidelines are still needed for proper and safe execution. Also, sport science distinguishes between different types of vertical jumps, each with its own course of motion: squat jumps (SJ), drop jumps (DJ), and countermovement jumps (CMJ) with or without an arm swing [11]. For the latter, research generally recommends starting in an upright standing position with the feet placed shoulder-width apart [16]. After a short downward phase mainly achieved by knee and hip flexion, the joints are brought into full extension while moving the arms in a forward-upward arc [39]. These mostly self-evident high-level descriptions of the different phases are complemented by specific evidence-based instructions to avoid excessive strain on the joints or boost jump height, e.g., squat depths at or less than 90 degrees yield the best performance [33].

Considering this plethora of task instructions, we see another potential use case of virtual surroundings: Providing 3D animations of the different jumps and their correct execution in an immersive environment likely fosters comprehension and allows for easier adoption into personal performance. Also, the previously proposed full-body tracking makes it possible to display an immediate replay of the user's latest jump, which can be visually compared to the guideline animation. Such a feature is especially valuable with regard to the concise and rapid execution of good jump performances. Hudson [41] compared different jump skills for differences in the underlying biomechanics. According to this research, experienced jumpers initiate extension of the different joints almost simultaneously with a temporal delay of less than 25 milliseconds. Further characteristics of well-executed movements are a short and powerful concentric phase and a proximal to distal sequencing of the body segments. Therefore, assessing the quality of an individual's jump with regard to these criteria is probably easier by viewing it in VR with the option to pause or slow the replay.

2.3 Feedback and Analysis

Apart from visualizing the user's performance in an engaging manner, we also see future potential in analyzing the recorded jump automatically and providing direct feedback. For instance, mistakes in the correct posture, such as a too shallow squat depth, might be highlighted in the replay animation and commented on for easier correction. Steering the user towards individual weaknesses not only benefits jump performance but can also help prevent injuries. Most jump-related accidents occur in the landing phase. For instance, hard or incorrect landings account for 60% of anterior cruciate ligament (ACL) ruptures among female high school basketball players [64]. A major risk factor is the vertical ground reaction force (vGRF) that occurs during landing. Excessive vGRF contributes to knee instabilities and can lead to ACL [38]. When comparing the two landings in a drop jump, athletes often exhibit greater side-to-side vGRF asymmetries during the second landing [6]. This observation indicates poor neuromuscular control in the landing phase, which is another risk factor for jump-related injuries [61]. Past research has demonstrated that precise instructions could immediately help athletes reduce their vGRF levels [55, 66]. Therefore, we assume that combining jump visualizations with automatic postural feedback can improve the users' execution for better performance and reduced risk.

2.4 Individual Training

After correcting postural mistakes during the vertical jump, athletes usually start training for greater strength and jump power. However, laypeople have difficulties identifying the proper exercises and routines to achieve optimal training results and boost personal performance. In general, jump training aims to improve the vertical take-off velocity, which is mainly achieved by increasing the extensor muscles' muscle force or contraction velocity [49]. Past research has indicated close relations between the jump height and both the maximal dynamic force of the lower extremities and the rate of force development (RFD) during knee extension [10, 73]. Vanezis and Lees [72] suggest that muscular strength and RFD have a greater impact on jump performance than the individual technique. Despite the major contribution of the lower extremities, jumping remains a full-body movement and should be trained as such. Carlson et al. [20] emphasize the importance of training the upper extremities to maximize the positive effect of the arm swing.

Even though a wide variety of training modalities for the vertical jump have been studied in the literature, including electromyostimulation [52], vibrations [19], plyometric training (PT) [1], and weight training (WT) [74], only the last two achieved consistent and reliable results [62]. Weight training, which is used to increase the maximal muscle force, improved jump performance between 2% and 25% depending on the study setup and the subject's proficiency [62]. The best results were achieved with light loads and high speed. Plyometrics are fast and explosive exercises, such as drop jumps or alternate-leg bounding [31], to improve the stretch-shortening cycle (SSC) [53]. Movements that rely mainly on the SSC, i.e., rapid and powerful concentric contractions followed by high-intensity eccentric contractions, especially benefit from PT. In these cases, performance improvements varied between 5% and 35% [62]. Instead of focusing on one type of training alone, recent research has emphasized the benefits of combining the concentric improvements through WT with the increased RFD and SSC achieved with PT to maximize training effects [48]. This combination outperforms single-type workouts significantly [29] and leads to better muscular composition [63].

Apart from deciding on the correct training modality to improve their performance, athletes also must choose specific exercises and workout routines. The necessary decisions about a training strategy also present further challenges. For instance, most people prefer to stretch before performing an athletic activity. However, static stretching has been shown to have a detrimental effect on jump performance and should instead succeed the training, while dynamic stretching can improve the short-term power output and increase neuromuscular activation [39]. Therefore, we assume that users might greatly profit from including training recommendations as part of the VR application. Depending on the particular performance, automatic suggestions could be presented after recording a jump. For example, players not using the arm swing to a full extent could focus on upper body drills first. Additionally, demonstrating the correct execution of each exercise minimizes the risk of training mistakes.

2.5 Motivation

The final possible area of application is the users' motivation. Lees et al. [51] proved that specific muscles, such as the hip joint extensors, work maximally only in maximal vertical jumps. Thus, submaximal jumps do not target the same muscle groups and lead to divergent training effects. Therefore, Bates et al. [6] suspended a basketball slightly above the maximum jump height to encourage participants to expend maximal effort. Similarly, we propose using the potential of virtual scenarios to motivate users to perform maximal jumps. Apart from displaying targets such as basketballs, it might be beneficial to scale the vertical displacement during a jump. This hyper-realistic concept has already been used for locomotion [75] and as an exergame concept [42], where it boosted the players' motivation. As jumping is not only used for performance tracking but also takes a significant portion of plyometric training, we see the potential of using an immersive experience for motivation. Like popular workout games, such as *BeatSaber* [7] or *BoxVR* [30], players could use a jumping game to train their vertical jump in a fun and engaging manner. Apart from the training context, the possibility to jump in VR might also promote the development of new full-body gaming concepts.

3 DESIGNING THE PROTOTYPE

After assessing the potential of VR-based training, including performance measurement and exercise recommendations, we designed a first preliminary prototype to demonstrate its practical use. We decided to use the HTC Vive Pro HMD [40] with SteamVR 2.0 Lighthouse tracking to benefit from the seamless integration of the Vive hardware trackers for full-body capture. For the scope of this work-in-progress paper, we mainly concentrated on three research questions:

(1) Can users perform a maximal vertical jump with a VR headset safely and comfortably?
(2) Is the existing tracking technology precise enough to record the users' movements during a vertical jump?
(3) How feasible is a VR-based training application for the vertical jump, focusing on measuring performance, visualizing recorded jumps, and providing preliminary postural feedback?

3.1 Participatory Design

As most of our open questions closely relate to the individual user experience, we applied a participatory design phase to incorporate feedback right from the beginning. Considering the hygiene measures due to the COVID-19 pandemic, we limited the participating users to four individuals (2 male, 2 female) with a mean age of 22.75 (SD = 1.71). None of the subjects were involved in this project but were at least generally familiar with VR systems. Additionally, two participants were active basketball players with amateur sports trainer experience. We arranged three sessions for each participant throughout the project to observe the individual experiences and collect oral feedback. The subjects' input was, if possible, implemented in the next iteration.

3.2 Jumping in Virtual Reality

Our first concern was the general safety of the users when performing the vertical jumps. Therefore, we provided a $16m^2$ obstruction-free space in our VR lab and did not use any trackers or controllers for the first jumps. Even though all participants initially stated slight reservations concerning the risk of injury, these concerns turned out to be unsubstantiated. The headset's position remained fully stable without inducing any tracking errors or blurry vision. Instead, even with glasses, the fit was generally described as comfortable. After few tests, each participant dared to perform vertical jumps with maximal effort. The only slight complaint issued by subjects was the cable between HMD and computer, which the supervisor monitored. Due to technical issues, we could not replace it with a wireless solution. Even though no subject felt restrained by the cable, all emphasized the potential additional comfort by replacing it.

After clearing our initial point of concern, we addressed the recording of the users' movements. Apart from head and hands, which are easily captured through HMD and controllers, dedicated Vive trackers are needed for all other body segments. These are usually fixed to the body using elastic attachments in the form of belts or ankle straps. However, experiments quickly revealed that in contrast to the HMD, the trackers fit too loosely. In consequence, the wobbling caused tracking errors or even connection losses. In the end, our trials resulted in using a chest strap, used for action cams, and 3D-printed adapters attached to the shoe lacings. In sum, we captured six stable and reliable tracking points: feet, upper back, hands, and head (see Figure 1). Even though legs and thighs are acceptably simulated by preconfiguring segment lengths, the suboptimal tracking still omits important postural data, such as knees caving inward. Therefore, we aim for more detailed motion capturing without impeding jump performance for our future studies.

3.3 Instructions

We realized our prototype application for recording and analyzing jumps with the Unity game engine [70]. The scene was designed to resemble a typical gymnasium to enhance familiarity. Following the proposed use cases of such an experience, we started by providing visual demonstrations for three jump types: squat jump, and countermovement jump with and without the arm swing. A primitive avatar performed the different phases of countermovement, jump, flight, and landing, while the corresponding movements were highlighted on the model and described on a wall-mounted chalkboard. Players could watch the instructions at their own pace and return to them between jumps.

3.4 Postural Feedback and Replay

Next, the subjects started the recording and performed their vertical jump. The jump height as the main performance measurement was defined as the maximal displacement of the trunk compared to the initial standing pose (see Figure 2). Further, we used the tracking data to split the recording into the respective phases and visualized these using the same avatar. We provided preliminary feedback for individual postural criteria, such as a parallel, shoulder-wide stance, a squat depth of at least 90° (±10°), the full extension of the body in midair, landing with both feet simultaneously, and bending the knees to absorb the shock. The fulfillment of the criteria was displayed on the chalkboard during the replay (see Figure 1). Finally, the subjects could start over and try to incorporate their mistakes in the next recording.

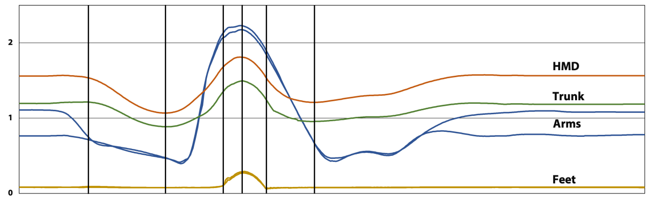

Figure 2: Line chart illustrating the vertical movements during a typical countermovement jump with arm swing. Lines mark the beginning and end of the countermovement, concentric movement, jump, and landing.

In general, the participants rated their experiences very positively. Despite being partly active basketball players, no one was directly able to fulfill all criteria. However, the individual mistakes eventually reduced over multiple iterations of jump recordings. We could not observe significant increases in jumping height after the initial familiarization, which is in line with past studies indicating that the neuromuscular pattern requires time to adapt to an altered technique or muscular strength. However, the subjects overall appreciated *"seeing their own mistakes and trying to correct them instantaneously"(**P2**)*. For future studies, they still recommended visualizing the postural recommendations right in the replay visualization to *"make it easier to locate areas of concern"(**P1**)*. Although the participants had no problems training jumps wearing the complete VR outfit, this finding does not apply to VR-based workouts in general. We asked the subjects to perform a series of physical exercises, such as planks, push-ups, or squats, for testing purposes. Especially movements that involved looking downward, like the plank, caused the headset to lose its initial tight contact with the face, leading to blurry vision. Therefore, we do not see any advantage of performing such exercises with a VR headset. Repeated jumps used in PT to improve the SSC might still benefit from boosting motivation with an engaging scenario.

4 NEXT STEPS

Our presented prototype demonstrates that even maximal vertical jumps are possible in VR without disturbing tracking or risking accidents. Although our preliminary motion analysis indicated further possibilities for jump training, the constrained tracker placement limits capture precision below the quality levels needed by professional athletes. Instead, we see the major potential in recreational sports. Similar to exergames like *BeatSaber*, such VR-based training allows players to improve their jump skills in an engaging way and thereby prevent injuries by enhancing general fitness and body stability. These training results are helpful in various sporting activities and also benefit occupational tasks [5, 47].

In the future, we aim to improve the current prototype by attaching more hardware trackers to achieve a more precise motion analysis. Further, we will use this information to provide more individual feedback regarding posture, coordination, and muscular deficits. For instance, measuring the initiation of muscle extension is possible with the existing capabilities and indicates the efficiency of neuromuscular coordination. In response to the participants' feedback, we will include a feature to track the individual progress over multiple jumps and exercise sessions. Finally, the performance analysis should result in a personalized recommendation of suitable training workouts and potentially an exergame component for executing these exercises in VR. Since such an application would mainly compete against other forms of unsupervised training, such as online videos, we plan to conduct a more extensive study comparing the resulting training effect.

5 CONCLUSION

The vertical jump is a complex multijoint movement requiring substantial muscular strength, postural stability, and neuromuscular coordination. It plays a fundamental role in many sporting activities and is also a commonly used indicator for general fitness. However, jump training is often neglected in recreational sports, and mistakes are hard to identify during the short and intricate movement. Therefore, we explored the potential of training the vertical jump in VR. Our identified use cases include comprehensive explanations, instant replays of recorded jumps, individual motion analysis, personalized exercise recommendations, and motivational scenarios. Further, we demonstrated the feasibility with an initial prototype, collected first-user receptions, and explained our future research steps.

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Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame

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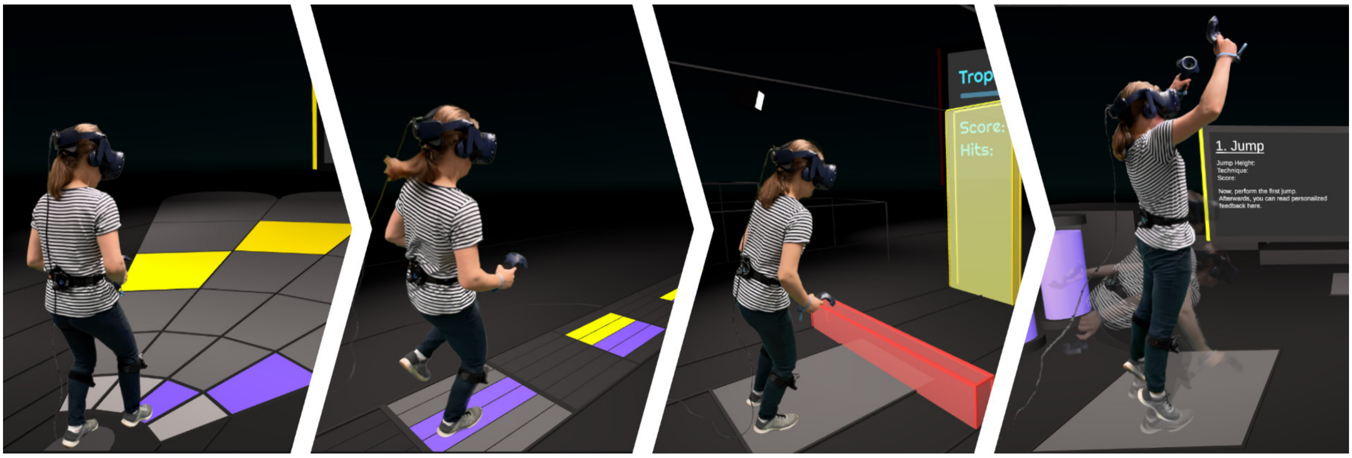

Figure 1: Demonstration of a VR-based full-body training with our exergame *JumpExTra VR*: In the first three levels (from left to right), players perform various movements, including taps, hops, and jumps, that train lower body coordination, stability, and endurance. Finally, the right figure shows a player, who trains maximal vertical jumps.

ABSTRACT

Virtual Reality (VR) exergames can increase engagement in and motivation for physical activities. Most VR exergames focus on the upper body because many VR setups only track the users' heads and hands. To become a serious alternative to existing exercise programs, VR exergames must provide a balanced workout and train the lower limbs, too. To address this issue, we built a VR exergame focused on vertical jump training to explore full-body exercise applications. To create a safe and effective training, nine domain experts participated in our prototype design. Our mixed-methods study confirms that the jump-centered exercises provided a worthy challenge and positive player experience, indicating long-term retention. Based on our findings, we present five design implications to guide future work: avoid an unintended forward drift, consider technical constraints, address safety concerns in full-body VR exergames, incorporate rhythmic elements with fluent movement patterns, adapt difficulty to players' fitness progression status.

*Both authors contributed equally to this research.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Empirical studies in HCI**; • **Software and its engineering** → **Interactive games**.

KEYWORDS

virtual reality, exergames, vertical jump, training, sport

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1 INTRODUCTION

Regular physical exercise is vital for our bodily and mental well-being. Athletic activities not only increase our overall fitness but can also delay the natural aging process [39] and even benefit the brain's cognitive functions [104]. However—because physical activity is strenuous on our bodies—many people hesitate to transition toward an active lifestyle and to create lasting exercise habits if they do not receive incentives [26]. Apart from popular approaches, such as peer-support or fitness trackers, exergames promise to motivate users by providing an engaging experience. In the virtual reality (VR) domain, fitness games are among the highest-grossing titles and a crucial reason for headset purchases [46]. The advantages are apparent: Affordable mobile VR headsets with handheld controllers allow players to combine enjoyable gaming activities with healthy physical exercise while staying in the comfort of their homes.

Exergames like Beat Saber [47] or BoxVR [43] use only head and hand movements for their gameplay because many current VR setups can only track a person's head and hands. Instead of providing balanced exercises to the entire body, the training effect of these titles is mostly limited to cardiovascular improvements and upper body fitness. As a result, players do not get the benefits of balanced full-body activities, such as improved coordination, stability, and balance [4, 105, 112]. Also, training only individual muscle groups can ultimately lead to muscular imbalances promoting bad posture [18, 69] and increasing the risk for injuries [32, 113]. Lastly, lower body exercises and physical activities like walking, running, or jumping are vitally important in our society because an average person spends most of their day sitting and moving insufficiently [126]. To make VR exergames more valuable as exercise environments, their traditional hand-focused gameplay must be adapted to incorporate activities for the lower body. While we currently do not know if VR exergames are as effective as gym classes or personal training, we know exergames provide a great motivation for exercising regularly without requiring dedicated training spaces [42, 85].

Unfortunately, using lower body or full-body movement in VR exergames introduces many challenges. These exercises have a higher risk of swift or unstable movements which might lead to dangerous collisions. Explosive movements, such as running or jumping, can suffer from poor tracking stability [62, 128], which negatively affects player experience. Full-body movements require expert knowledge for safe training because they are more complex than simple arm swings in Beat Saber [47] and bear a greater risk of injury or wrong execution. Limitingly, existing design guidelines and best practices primarily target physical exercises and movements for non-VR exergames [88, 97, 98].

Our research fills this knowledge gap by following the feedback from domain experts to create a full-body VR exergame. We focus on one particular use case: training people's vertical jump performance using a VR exergame. We chose the vertical jump exercise as our full-body movement because of the following reasons: Jumping is a fundamental human movement that is not only required for many sports, such as basketball [33] or volleyball [109], but is also used to assess general fitness [50], body composition [15], and coordination [91]. Vertical jumps are a perfect, yet challenging, core movement for our research. They also work inside the tracking areas of current VR headsets. At the same time, vertical jumps are a highly explosive movement that challenges tracking stability.Finally, jumps can be improved through many training modalities and combined with other movements to achieve a diverse exercise experience.

We focus primarily on improving general fitness and motivation through training. For this, we conducted a semi-structured interview with experts from different domains (e.g., sports research or physical therapy). We discuss the potential benefits and challenges of VR-based jump training identified in our thematic analysis and provide guidelines for structuring gamified training routines. We developed a VR exergame to train the vertical jump based on these insights. In our design process, we closely follow the recommendations of experts. In particular, our exergame is composed of four levels of increasing difficulty to prevent injuries and foster the learning process (see Figure 1).

In the last part of our work, we investigate how users perceive our exergame prototype and what implications can be drawn for future designs and research projects. As our first step, we conducted an exploratory study with 25 participants to evaluate how users perceive this new training experience. The results confirm that our jump-centered exercises provided a worthy challenge and led to a positive player experience. Our study also revealed the technical limitations of current VR systems, and participants provided substantial suggestions for improving the training experience. Subsequently, we condensed these insights into design implications and lessons learned.

First, we discuss potential safety issues. In our case, frequent jumps on one spot often led to an unnoticed forward movement—the unintended forward drift—which eventually leads to players leaving the intended play area. Hence, we recommend particular care to avoid dangerous collisions, especially when other non-stationary movements, such as forward jumps, are used.

Next, we examine the design implications arising from technical limitations of current VR systems. Slipping hardware trackers and insufficient tracking accuracy challenged the precision of our individualized jump feedback. Therefore, we recommend empowering users towards self-correction (e.g., by visualizing a replay of their movements) and supporting this process with automated feedback.

Finally, we talk about our efforts to provide a pleasant game experience and increase replayability. Above all, participants praised the gamified fitness exercises in the first three levels. We discuss lessons learned for enabling a natural and fluent movement sequence, such as the suitability of different patterns (e.g., the "walking style") or incorporating frequent resting periods. We emphasize the importance of aligning the difficulty with the players' capabilities and improvements. In particular, beginners profit from adapting the difficulty automatically.

The main contributions of this research are:

(1) Identification of the benefits and requirements of VR jump training through semi-structured interviews with domain experts,
(2) Designing and developing a VR exergame prototype for training the vertical jump: *JumpExTra VR*,
(3) An exploratory study to evaluate the feasibility of our exergame as a training tool, and
(4) A set of design guidelines and lessons learned for developing full-body VR exergames.

Our explorative exergame study and the resulting five design guidelines (unintended forward drift fix, technical constraints consideration, safety concern mitigation, rhythmic elements using fluent movement patterns, difficulty adaptation to players' fitness level) constitute a first step to the creation of safer and more engaging exergame VR training environments. Our findings help players train effectively and without the risk of injury in small spaces using immersive technology. We believe this represents one possible future of technology-augmented sports exercises.

2 RELATED WORK

Our exergame design builds on two domain knowledge sources: prior research and expert interviews. Therefore, we introduce VR-based training, the relevant biomechanical foundations of the vertical jump and provide an overview of the related research on jump training, jumping in VR, and exergames in general.

2.1 VR Training

Using immersive experiences for training offers unique benefits and allows users to assess and improve their individual performance effectively [20, 119]. Especially when physical training at the target location is difficult or dangerous, like for pilots [52] or firefighters [111], VR applications can provide an accessible alternative [64]. In recent years, VR-based training has been successfully applied to many domains, including healthcare [87], medicine [3], and navigation [90]. In sports, VR has been used in research projects to analyze athletic performances [10, 30] and understand motor and perceptual skills [25, 31, 40, 129]. Furthermore, VR works well for training movement patterns, like golf swings [67] or dance moves [38], and improving hand-eye coordination (e.g., for table tennis [94], darts [116], or juggling [76]). Similarly, VR training can also support rehabilitation for stroke or cerebral palsy patients [27, 71, 96].

Besides boosting motivation, virtual experiences also have benefits for sports training. VR improves observational learning by displaying correct action patterns immersively compared to traditional computer applications [115]. Especially for sports, stereoscopic information is essential to trigger the correct motor responses [81, 127]. Additionally, mobile headsets also provide an easy way of monitoring the own performance [100]. For availability, VR applications can—to some degree—eliminate the need for specialized sporting equipment, dedicated training environments, or workout partners [94]. Adaptive training routines [37] and personalized feedback increase the individual gain and can complement professional trainers [70]. Despite these benefits, the effectiveness of VR applications for sports training remains an open research field. While studies have shown a positive impact on the execution of a particular exercise, the transferability to actual activities is not guaranteed [6, 77]. VR training can improve real-world skills for some use cases [12, 22, 93], but others cannot profit in the same way [73] and might even suffer from reduced performance [117].

2.2 Jumping

Jumping is a fundamental motor skill humans learn at an early age and improve upon throughout their lives. While most people do not jump regularly in their day-to-day lives, jumping is used in sports, fitness, and rehabilitation. In particular, jumps are a good indicator of a person's general fitness level [50], neuromuscular coordination [91], and muscle composition [15]. Apart from being required for typical jumping-intensive sports, such as basketball [33],jumps are used in rehabilitation to measure changes in pathology [53, 54] and predict the individual risk for injuries [23]. Aside from the positive effects on athletic performance [20, 108], jump training can also benefit daily activities and occupational tasks [8, 74].

2.2.1 *Composition and Execution of the Vertical Jump.*

Jumping is a "complex polyarticular dynamic movement requiring intermuscular coordination" [106] with typical execution times of less than 4 seconds [120]. The literature differentiates between various types of jumps [13], including squat jumps, drop jumps [61], or *countermovement jumps.* In the scope of this paper, we focus on the last type. It is typically initiated from an upright standing position [19], followed by a brief downward phase before the upward impulse is generated by extending the body explosively and swinging the arms in a forward-upward arc [57].

Jumping can exert high loads on the lower body's joints and tissues, increasing the risk of injury (e.g., ruptures of the anterior cruciate ligaments (ACL) [107] caused by hard or incorrect landings that lead to high vertical ground reaction forces (vGRF) [55]). Proper instructions can help athletes reduce the vGRF immediately [92, 110]. Other risk factors, such as the athletes' joint stiffness [35] and maturity [78], cannot be eliminated as easily with proper form.

2.2.2 *Jump Tests.*

Measuring a person's jump height is not a trivial task. Professional athletes and researchers often rely on motion-capturing systems [7, 9, 79] or dedicated vertical jump tests [72]. One of the oldest techniques is to jump next to a wall and mark the highest reachable points while standing and jumping. Then, one can calculate the effective jump height from the difference between both points [63]. Whereas this jump and reach test follows a simple principle, it also splits the athlete's attention and limits arm movement, which easily reduces performance. Another approach is to jump on force platforms and calculate the jump height from the athlete's airtime [15]. However, athletes can easily distort the result by flexing their legs to delay ground contact [72]. Instead, the most precise results are achieved by measuring the vertical displacement of the athlete's center of mass [120]. Consequently, our VR application can easily and comfortably measure the user's precise jump height by using a hardware tracker attached to the user's hip.

2.2.3 *Jump Training.*

Critical for improving jump height is increasing an athlete's take-off velocity. Training usually concentrates on improving the extensor muscles' forces and contraction velocity [75] because the maximal dynamic force of the lower extremities

Figure 2: The design process followed in this research project: we reviewed the literature, conducted semi-structured interviews with multiple experts, analyzed the requirements of VR jump training application, designed and implemented the VR exergame, and conducted an user study to test *JumpExTra VR*.

and the rate of force development (RFD) directly correspond to the final jump height [11, 123]. A well-timed arm swing [21], good neuromuscular control to initiate joint extension with minimal delay [60], and a countermovement with the optimal squat depth [48] have all been shown to improve jump height significantly.

Various training modalities have been found useful in achieving lasting training results. Firstly, plyometric exercises [2], such as drop jumps or alternate-leg bounding [44], improve the muscles' stretch-shortening cycle (SSC) and are primarily beneficial activities that involve rapid concentric contractions and high-intensity eccentric contractions [86]. The positive effect on jump performance has been extensively researched [13, 83] and varies between 5% and 35% depending on the athletes' proficiency [106]. Alternatively, athletes may conduct weight training [124] with heavy loads to increase the maximal dynamic strength [45] or light loads for explosive movements [84]. For jump training, the best results were reported using light loads and high speeds and range from 2% to 25% [106]. Some muscles, such as the hip joint extensors, are used only maximally in maximal jumps.Performance should be trained using maximal jumps to achieve the best training results [79].

2.3 Jumping in VR and Exergames

Jumping in virtual and mixed reality has also been the subject of other research projects. Prior literature has approached jumping in the context of locomotion [51, 82, 125], exergames [41, 62, 65, 80] or training [28]. Wolf et al. [125] presented an augmented locomotion technique where users performed physical vertical jumps, which translated into hyper-realistic forward jumps in VR. Their findings indicated that hyper-realistic jumps can enhance some factors of user experience (e.g., immersion). A recent work [28] presented a prototype of a VR jump training where players jumped and received feedback on their performance.

Exergames are one of the most popular types of games in the VR gaming community (e.g., Beat Saber [47]). Despite the potential drawbacks associated with the use of VR exergames (e.g., cybersickness [114]), we see these games as an opportunity because they offer fun, physical activity, and accessibility to training regardless of location or health condition [66]. Although there are some exergames that feature full-body training [65, 89], the majority focus on upper body exercises [14, 47, 66]. Whereas this focus may be even preferable in some cases (e.g., due to safety [66]), full-body training could benefit more muscle structures, and has not been widely explored yet [89].

Several researchers have used jumping in their games. Finkelstein et al. [41] designed an CAVE-based exergame, *AstroJumper*, for children with autism. In the game, the players performed jumping movements to avoid objects, and the initial findings with neurotypical players indicated positive experiences. Kajastila et al. [65] examined the impact of three conditions on players' learning trampoline skills. The authors showed that the players were more engaged in the gaming conditions (a trampoline-based mixed reality game with and without exaggerated jumps) compared to the self-training condition, but their performance improved regardless of the conditions. Similarly, another study [80] designed and tested a multiplayer mixed reality trampoline game in a field study. The results indicated positive player experiences (e.g., autonomy and physical activity enjoyment). Many jump-based exergames have focused on player experience rather than providing a structured physical training for jumping using VR exergames. This paper extends the previous work [28] by designing and testing a detailed jump training VR exergame, *JumpExTra VR*, and involving the domain experts in the process.

3 THEMATIC ANALYSIS OF EXPERT INTERVIEWS

Unlike the prior literature, our research was not only on professional athletes and their sports performance training but we focus on the motivation of players to exercise. We gathered information from experts in the sports and medical field through semi-structured interviews to design and implement *JumpExTra VR*.

After internal discussion, the first authors created the interview questions and selected areas of expertise for interviewees, such as sports physicians and trainers. Based on these decisions, they selected several experts and invited them to this study via email. Nine experts from different domains (i.e., sports research, physiotherapy, and training) were recruited for the interviews. Given the variety of domains, they roughly followed their initial interview guidelines, but occasionally deviated from these questions to account for the specialties of the experts. The interviews were conducted using a video conference tool in German and took 42.4 minutes on average. The complete list of the translated interview questions can be found in the supplementary materials.

To prepare the interview data for analysis, we used the Dovetail [36] software for transcription. One of the first authors checked these transcriptions to correct and cut unnecessary details. Then, these texts were translated into English using DeepL Pro [34] and then checked again for any errors. To analyze the interview data, we used characteristics of both reflexive and codebook approaches of thematic analysis [16, 17]. Before the analysis, the first authors identified deductive categories related to the research questions: *execution*, *importance of jumping*, *safety in jumping*, and *jump training*. Then, these two authors independently and inductively coded the interview in groups, using descriptive codes (e.g., "correct execution of a counter-movement jump with arms", "landing is a major source for injuries", and "few short term improvements") under these categories. The groups consisted of two interviews in each and three interviews in the last one. After each group, the first authors met to discuss discrepancies between their coding and each author's understanding of the data. This process led to the creation, refinement, combination or exclusion of codes. Following the last group of interviews, the first two authors developed initial themes by creating a affinity map from those codes. Finally, they discussed and reshaped the affinity map and these themes in several meetings, which led to the formation of the following four themes.

3.1 Theme 1: Jumps are mainly used in sports and have numerous benefits for general health.

Both in everyday life and sports activities, we *jump*. However, the actual form depends on the particular context, as "*[...] we don't jump that often when we go shopping in the supermarket, we probably walk more. But of course you also have situations in which you might jump down in everyday life*"***(E3)***. Instead, jumps are mostly **integrated into compound movements**. For example, they might be combined with forward or side movements to dodge obstacles. Especially in sports, jumps are mostly incorporated into bigger movement patterns, such as block jumps in volleyball.

We perform jumps because they have several benefits for general health. The jump movement activates multiple muscle structures and allows us to exercise all of them at once. Moreover, it can help to improve fundamental human skills like **coordination**. A good execution requires the jumper to "*[...] coordinate the impulse from the arms with the impulse on the legs [...]*"***(E2)***. A physiotherapist emphasized the importance of jumps for **injury prevention** and gave an example of why it can help us: "*If I am an untrained person and I trip over a curb I could twist my ankle. But if I have trained [to jump] and [thereby] manage to activate my muscles quickly, I might be able to stabilize my body in time so that this accident doesn't happen*"***(E6)***. Despite this potential for injury prevention, jump training rarely finds applications in rehabilitation because health insurance often covers "*only the bare necessities*"***(E6)***. By jumping, the risk of some physical health conditions, such as "*osteoporosis*"***(E2)***, can be decreased. Interestingly, jumping, in fact, might be a helpful tool to trigger the regrowth of bones for older adults with reduced bone density. However, it might also be dangerous as "*maybe they don't have the stability yet to catch themselves and break away*"***(E5)***. Therefore, most experts indicated that jump training is generally not favorable for older adults. In particular, one expert pointed out that alternatives should be considered to reach similar benefits: "*Do jumps then make much sense or don't you achieve that rather, for example, with more strength training equipment?*"***(E2)***.

In general, we mainly use jumps for **testing, training, and in sports games**. First, jumps are a good instrument to test people's performance, and can lay down a foundation to understand "*[...] the rate of force development, i.e., how quickly can I generate force, which is well represented by jumps*"***(E1)***. However, the primary application of jumps lies in the actual gameplay. Especially in certain sports such as basketball and volleyball, jumping can be a decisive part of the game. For instance, an interviewed basketball trainer noted that a good jump performance could be a game-changing advantage for some players: "*Jumping power itself is particularly relevant in basketball because you can compensate for your physical size a bit, if necessary*"***(E7)***. Finally, using jumps in training, e.g., for volleyball, can be beneficial to improve the fatigue capacity: "*Someone who practices a lot and is well trained in jumping can hold the jump height much longer with a lot of jumps before it gets less*"***(E1)***.

3.2 Theme 2: Jump training combines reactive and strength exercises. Incorrect executions of maximal jumps leads to injuries.

Domain experts frequently gave the obvious answer to how to best train for better jumps: "*by jumping*"***(E1)***. However, apart from this conspicious statement, it is essential to frame individual exercise goals: increasing the jump power requires different training concepts from working on the jump technique.

Jump power is mainly determined by the muscles' rate of force development. Hence, it can be improved through various training modalities. In particular, **explosive movements** and **speed-based exercises** are especially effective. An interviewed basketball trainer described a typical reactive training they regularly performs: "*We put several [boxes] in a row behind each other and did bounce training there with our legs closed. Always both feet on a box and then further, up, down, up, down and so moved through the hall*"***(E7)***. Additionally, exercises that target the muscles' lift capabilities, e.g., traditional strength training, also improve the overall jump height. Also, the experts recommended **combining jump training with other physical exercises** and including "*different variations*"***(E2)*** as jumps are usually not performed in isolation. Unfortunately, short-term improvements are not to be expected as changes in muscle mass and composition typically take many weeks: "*It usually takes 4 to 8 weeks minimum, until you can really prove something muscular or microscopically*"***(E5)***.

Even though small hops are generally unproblematic, most experts agreed that the maximal vertical jump is a highly complex and error-prone movement. Thus, the foremost goal of maximal jump training should be **correct execution**. Given the variety of used jump techniques, we explicitly asked the experts about the correct execution of a countermovement jump with an arm swing. This movement is typically executed by starting in an upright shoulder-wide stance. After a quick downward movement, the athlete extends their body explosively. The arms swing in an upward arc and are stopped roughly at chest height before the feet lose contact with the ground: "*If I want to jump to the maximum, I actually have to slow the arms down at shoulder height and at the right moment*"***(E2)***. Despite this general routine, the individual body shape and the sports context can lead to differences in the execution. For instance, athletes cannot reach lower squat depths if the gluteal muscles are not strong enough.

Most experts deemed **landing** after a jump the major source of **injuries**. A particular pain point is the knee movement. The knees should always remain in one line between the ankle and the hip. However, high-impact forces can cause the knees to collapse medially. This knock-knee position is perilous and puts extreme pressure on the knee and the surrounding ligaments. Apart from a weakly developed musculature, gender differences contribute to this condition as females are generally more prone to having knock-knees: "*There are also anatomical reasons, it's a little bit due to the hip* *position of women"(**E2**).* Lastly, preinjuries can increase the risk of further accidents while jumping. Apart from an incorrect landing, the experts mainly attributed the **exercise environment** as an important injury factor and suggested using a mat as a protective measure. In contrast to the muscular changes, improvements in jump execution are quickly achievable but hard to quantify. One expert proposed measuring the knee deviation during landing as a possible improvement.

3.3 Theme 3: Jump training should increase gradually and account for individual differences, goals, and improvements.

In contrast to general physical activity, training is always **goal-oriented** and consists of exercises that exert a sufficient stimulus to trigger progression, such as muscle growth. However, our interviewed experts underlined the importance of carefully weighing training intensity, repetition count, and recovery time to maximize improvements and avoid injuries. Special attention should be placed on beginners who are not regularly exercising. For instance, "*if they are not used to it, [their knees and ankles] are very susceptible to evasive movements"(**E5**).*

As the risk of injury depends primarily on the range of motion, training should **start with simple exercises**, such as mini hops, before gradually increasing the difficulty. Doing so also has another advantage: many experts agreed that small jumps are generally safe and do not require a prior warmup. In contrast, intensive or longer training sessions should be preceded with warmup movements, such as small hops, to prevent muscle strains. One expert whose research focuses on people with special needs proposed to even start with simple steps to make the application accessible for users with coordination and balance problems: "*So before it's even about doing a jump. To first step over an obstacle, sometimes with the right, sometimes with the left, in order to promote balance"(**E9**).*

Apart from **adapting** the **training difficulty** according to the users' abilities and fitness level, experts also emphasized the importance of **providing proper feedback**. Guiding the users and building competence is vital for sustainable training results. One interviewed sports didact reported the benefits of recording the users' movements "*so that [they] can see their own jump to create a movement image of themselves"(**E3**).* Combining this intrinsic learning with extrinsic feedback is particularly useful for continuous improvements. Additionally, the experts recommended focusing primarily on repetitive situations that permit users to incorporate their insights in the subsequent execution.

3.4 Theme 4: VR jump training can provide real-time feedback and boost motivation. Yet, safety might be an issue with VR.

In general, all experts saw potential benefits and challenges in using VR for jump training. Firstly, a major advantage of VR and AR is the ability to provide directly applicable **real-time feedback**. Also, whereas some experts recommended using mirrors or video recordings to show the users their movements, many people do not like seeing themselves. In this case, seeing a replay of their own jump might be even counterproductive: "*Of course, it's not helpful at all to then replay a video of the own moves that aren't working out"(**E3**).* VR can help avoid such potential alienizing effects by introducing an additional abstraction layer. For example, users could see a generic avatar performing a replay of their jump.

Furthermore, VR exergames could benefit mental well-being by improving mood, reducing stress, and increasing the users' **motivation to train**. In particular, one expert suggested that gamified exercising might provide similar strong incentives like peer support and outperform wearables, as "*just a fitness tracker [...] can only change something, if so, in the very short term"(**E4**).* However, as we have seen with popular augmented reality (AR) exergames, such as Pokemon Go [102], the interest in such titles can decrease over time.

Finally, the experts raised concerns regarding the **safety** of VR-based jump training. For instance, a mismatch between the feedback from the virtual world and the physical movement likely causes cybersickness and could even lead to dangerous situations. Therefore, it is necessary to consider potential issues early in the design pipeline because "*if [...] the risk of falling or somehow feeling unwell is greater than the benefit I generate, then it's immediately a problem"(**E1**).* Lastly, one expert expressed doubts about whether VR should be used to measure the jump height, as there are likely more affordable and precise approaches.

4 EXERGAME: JUMPEXTRA VR

Based on the insights from our expert interviews, we designed a VR exergame with the Unity game engine [118] to train the vertical jump. Our primary focus was on motivating players to exercise in a gameful way (i.e., using the motivational pull of games). However, we also wanted to avoid any injuries or frustration by aligning the gameplay with the players' capabilities and giving constructive feedback to assist them in improving their jump.

The first challenge for implementing a jumping-based exergame is tracking the entire body's movements because most VR systems use only an HMD and tracked controllers. We experimented with various approaches throughout our design process, such as using a Kinect 2 for Windows [95]. However, the high latency and inferior tracking quality when jumping made markerless motion capturing an undesirable choice for our use case. Instead, we opted for using a Vive Pro [58] and attaching Vive Trackers [59] to the players' shins and waist. Even though tracking players' feet was our initial first choice, our pilot tests revealed that placing the trackers on the shins drastically improves tracking accuracy and comfortability. Together with the controllers and headset, we used a total of six tracking points to animate a virtual avatar using inverse kinematics.

4.1 Rhythmic Levels

Many experts emphasized the importance of raising the difficulty gradually by starting with small hops before attempting higher jumps. This design not only prepares players for more intensive sections but can also serve as a warmup. In contrast to maximal jumps, small hops have a negligible risk of injury. One expert, who focuses on user groups with special needs, raised the concern that some players might not be ready for hops at all since the frequency someone uses jumps mainly depends on their exercise practice.

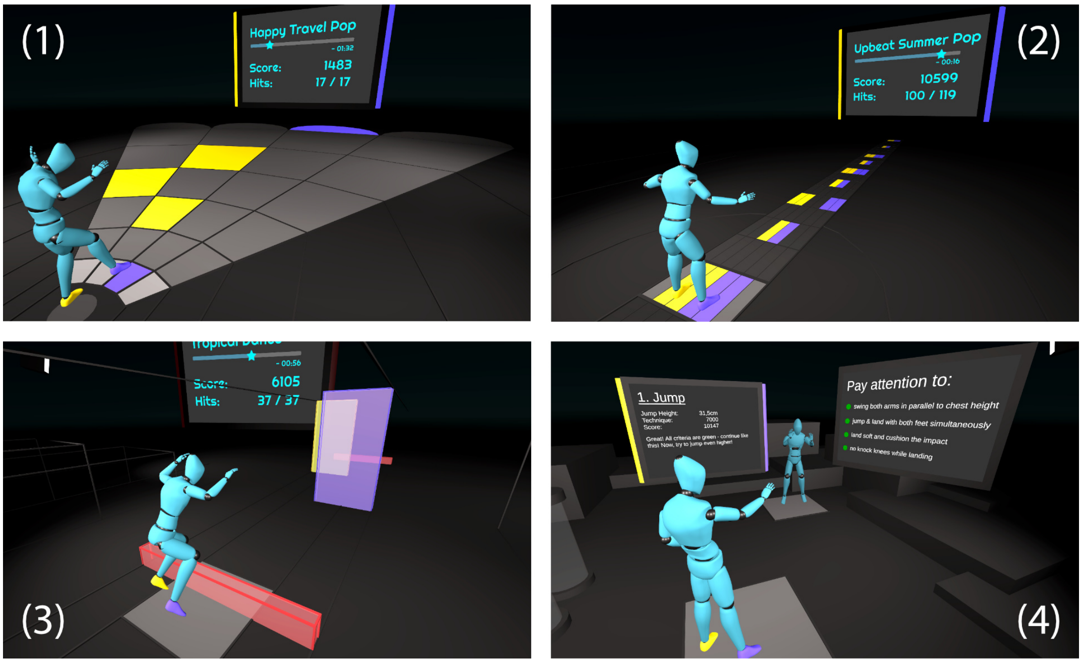

Figure 3: Our exergame *JumpExTra VR* features four sequential level. In the first level, players tap on colored tiles with their feet. The second level features a hopscotch game. In the third level, players avoid obstacles. In the last level, players train their maximum vertical jumps and receive personalized feedback.

Instead, the expert proposed starting with steps and balancing exercises before continuing with hops and larger jumps. As our goal was to design an engaging experience for everyone regardless of prior experience, we decided to structure our game into four sequential levels, starting with tapping before increasing the intensity by incorporating hops, small jumps, and finally, maximal vertical jumps (see Figure 3).

The first three levels are structured similarly and tie the players' actions to the beats of a song. Such rhythmic movements are suggested by the literature [97] and have been used with great success in some of the most famous VR games, such as Beat Saber [47] or Ragnaröck [121]. Whereas all levels feature a different song, the length is always roughly two minutes with 128 beats per minute. Before starting the action, players receive a short introduction to every level and must perform each relevant movement correctly. During the level, a large screen in the background displays the song progression and the players' performance, measured in successful hits and a derived score. Also, the game provides motivational feedback in the resting break between the levels.

To account for individual differences and fitness levels, we implemented three difficulty levels differing in the number and complexity of necessary movements. Starting at the lowest difficulty, the game automatically and unnoticeably switches to a higher level if players achieve a precision of at least 90% or to a lower level if they miss more than 40% of the last notes. With this design decision, we want to ensure that the game challenges all players without causing frustration. Ultimately, we aimed for an average hit rate between 60% and 90%. With this adaptive difficulty, we ensured that most players would achieve a high overall score boosting their motivation and confidence.

Level 1: Tap to the Beat. In the first level, yellow and purple tiles approach the players on four adjacent lanes. As the tiles reach the front line, players must tap on them with the correct foot — yellow tiles require the left foot, whereas purple tiles map to the right foot. After tapping, players must retract their feet as they must not enter the playing field with both feet simultaneously. In the course of the song, the movement patterns become more complex and require players to switch feet quickly or tap crosswise. This level is mainly intended as a warmup and trains the players' lower body coordination, stability, and reaction time.

Level 2: Hopscotch. The second level advances on the first one by incorporating small hops. Similar to the child's game hopscotch, players have to hop with their left, right, or both feet on the correct tile. However, these hops are performed in place as the approaching tiles reach the players' position. The tiles move on five overlapping lanes, of which either one or two light up in yellow or purple to indicate the correct feet. Players must remain in the last pose between two hops, e.g., standing on one leg until another tile reaches them. Throughout our design phase, we learned that longer phases on one leg and fast switches between two and one leg are highly challenging and often do not fit the music. Instead, we mainly used slower two-legged jumping patterns or faster one-legged "walking-style" patterns. As before, the movement becomes more complex with time and incorporates the outer lanes more to force players to move from side to side. This second level builds on the already trained balance and stability. Also, players must time their hop correctly to land on the tile when it lights up. This feature further trains coordination and neuromuscular control.

Level 3: Obstacle Course. The last song-based level follows a different principle than the first two. This time, obstacles approach the players at every first beat of a bar. To gain points, players must avoid touching these impediments with their bodies. The most common obstacle is a low wall forcing players to jump at medium height. As our domain experts emphasized the importance of diversified training and dynamic exercises, we interleave the jump-over obstacles with lateral walls to both sides and barriers hanging from the ceiling. These force players to move sideways and duck down before jumping again. As personal size differences could pose an unfair disadvantage due to height differences, we scale the lower and upper walls according to the players' height during calibration. Also, the three difficulty levels affect only the obstacle size, not their frequency. Consequently, players must jump higher with increasing difficulty. This third level mainly focuses on muscle strength and endurance while preparing the players for the last level featuring maximal vertical jumps.

4.2 Maximal Vertical Jumps

After training the prerequisites for a good jump — general fitness, balance, and coordination — our last level focuses on teaching players a proper jump technique. In the beginning, players see an exemplary jump execution as part of a short introduction to the level. Next, players have to perform maximal vertical jumps and receive personalized feedback on their performance. The game continuously records the players' movements. After detecting a jump, this data is analyzed with regards to four criteria of a safe and efficient jump that the domain experts mentioned:

- jump and land with both feet simultaneously
- land softly (forefeet touch the ground first) and absorb the impact with the entire body
- especially while landing, keep the knees in one line between feet and hips and do not cave them inward
- swing arms synchronously in a forward-upward arc until about chest height

To account for tracking imprecisions, we implemented offset values until a violation of the above factors is considered insignificant based on our pilot tests. After performing a jump, players see their performance in the four categories on one screen and receive a personalized message on another. This message summarizes their improvement from the previous jump, their worst-performing criterion in this jump, and practical instructions on how to improve on it in the next turn. Additionally, we visualize the last jump as a looping replay in front of the players, which allows them to study their movements. Multiple experts deemed combining extrinsic instructions with the opportunity for intrinsic feedback through jump visualizations highly valuable.

Apart from providing personalized instructions, we also calculate a jump score from the technical criteria and the effective jump height to reflect the performance. Together with the jump height, this value is listed on a highscore board, informing players of their improvements from jump to jump. In total, players perform five consecutive jumps and try to incorporate the feedback to improve their performance with each jump. After the last jump, the game ends.

5 EVALUATION

After designing our exergame *JumpExTra VR*, we conducted an exploratory user study to explore how users perceive our novel training experience. Our primary research goal for our study was to confirm that our prototype provides an enjoyable user experience without causing unwellness or endangering players. Since players constantly remain in one spot through the experience, we are confident that the application is not likely to induce cybersickness. Additionally, we are interested in how the game's usability, appeal, and feedback contribute to the players' overall game experience.

Apart from these perceptional factors, we want to explore our exergame's motivational and physical effects on the players. Firstly, following our experts' feedback, we assume it improves the players' mood. Also, we hope that the players find the game's physical exercises challenging without frustrating or overly tiring them. Consequently, we are interested in how players perform in the various levels and where they see the future potential of such an exergame-based jump training.

Considering these motivations for our exploratory study, we employed various methods, including pre- and post-questionnaires, game performance data, and qualitative feedback, to answer our hypotheses and research questions:

- H1: Our exergame does not induce significant cybersickness.
- H2: Our exergame significantly improves the players' mood.
- RQ3: How do players evaluate the player experience of our exergame and its usability as a training tool?
- RQ4: How do players perceive the physical activity and perform in our exergame?

5.1 Pre-Post Questionnaires

These questionnaires were administered before and after the gameplay. To answer H1, we administered the simulator sickness questionnaire (SSQ) [56, 68]. It measures three sub-categories, i.e., nausea, oculomotor disturbance, and disorientation, through 16 items on a 4-point scale. For H2, we assessed the players' mood with the energetic and valence sub-categories of the German version of the Multidimensional Mood Questionnaire (MMQ) [122]. The scale consists of four bipolar items on a 7-point Likert Scale (ranging from 0 to 6).

5.2 Post-Questionnaires

To measure the general game experience to answer RQ3, we used multiple sub-categories of the German version of the Player Experience Inventory [1, 49]: mastery, immersion, progress feedback, audiovisual appeal, challenge, ease of control, clarity of goals, and enjoyment (7-point Likert scale, ranging from -3 to 3). Additionally, we used the physical activity enjoyment scale (PACES-8) [99] for RQ4, which includes eight bipolar items on a 7-point Likert scale (ranging from 1 to 7). The German item translation of PACES-8 was provided by one of the researchers, who used this scale in another research project [under submission].

5.3 Game Performance Measures

As we were interested in how players perform in our exergame to answer RQ4, we logged the necessary performance data for all participants. For each of the first three rhythmic levels, we recorded the difficulty development throughout the song and the hit ratio, i.e., how many steps, hops, and jumps over obstacles were successfully performed. Additionally, we collected the particular jump height and the performance in the four jump criteria for each jump in the final level.

5.4 Qualitative Feedback

We gathered qualitative feedback from the players through open-ended questions to understand their detailed experience with *JumpExTra VR*. In these questions, we particularly focused on four topics: risks and benefits, safety and usability, long-term participation, and improvements. We used the following open-ended questions to capture the perspectives of the players on these aspects:

- *"In your opinion, what are the risks and benefits of this VR game for you? Why?"*
- *"Have you encountered any issues that affected your safety and usability during the VR gameplay? Why?"*
- *"If you could continue to use this VR game, how do you think that this would affect your long-term participation in jump training? Why?"*
- *"Considering the VR game you played, what aspects would you like to change, and what aspects would you like to keep as they are? Why?"*

6 RESULTS

Twenty five participants (15 female, 10 male, *M*=24, *SD*=6.01 years) were recruited for our study. Twenty of them had prior VR experience. However, only two reported using VR frequently (1-2 times per month). Of the rest, twelve participants rarely used VR devices (1-2 times per year), and the remaining had only one to two prior sessions. Asked for their exercising habits, only two participants stated not to be exercising. Among the rest, ten participants exercised one or two times per month at most. Eleven reported exercising at least once per week, and two trained daily. Additionally, the participants generally rated physical exercise enjoyment slightly positive (*M*=1.24, *SD*=1.45, range -3 to 3).

After learning about our research objectives and signing informed consent, participants completed the first part of the questionnaire, assessing demographics, pre-SSQ, and mood. Upon completion, we introduced the participants to the Vive Pro VR headset [58] and assisted them in attaching the Vive Trackers [59] to their shins and waist. After starting the game, the participants received an introduction to the controls and calibrated their avatar before playing the four levels. After the playthrough, they completed the entire post experience questionnaires and answered the open-ended questions. The duration of the study was 35 minutes on average.

6.1 Pre-Post Questionnaires

We conducted Shapiro-Wilk tests to check the normality assumption of the data. When the data was normally distributed, we used

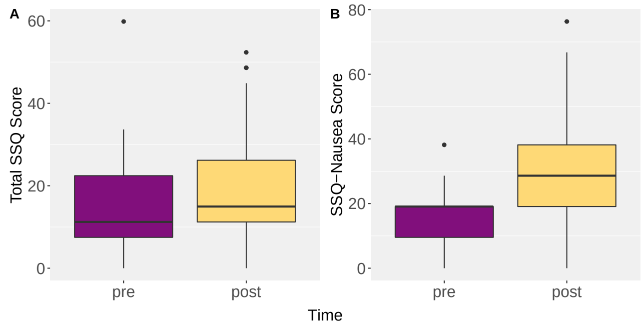

Figure 4: Although the participants' Total SSQ ratings was not significantly different between pre- and post-time points, post-SSQ-Nausea scores were significantly higher compared to the pre-SSQ-Nausea scores.

paired t-tests and reported the effect size with Cohen's *d*. In the case of non-normally distributed data, we used Wilcoxon-signed rank tests and reported *r*, Pearson's correlation coefficient, as the effect size measure. We followed Cohen [29]'s recommendations to intepret these effect sizes. Table 1 lists the results of statistical tests as well as descriptives of each questionnaire and their sub-categories.

A wilcoxon-signed rank test indicated that participant's post-nausea scores were significantly higher than pre-scores, *V*=4.5, *p*<0.001, Figure 4b. However, Total SSQ scores and the other sub-categories of SSQ did not indicate significant differences between pre- and post-values.

Due to the nature of exercise, people tend to sweat. Whereas sweating can be considered a symptom of cybersickness, in our case, it is more likely an effect of the physical effort during training [5]. Therefore, we also performed the SSQ questionnaire analysis while excluding the sweating item. Since this item is considered only in the calculation of Total SSQ and SSQ-Nausea categories, we report only their analysis. Total SSQ scores were not significantly different between pre- (*M*=12.42, *SD*=13.30) and post-time points (*M*=12.42, *SD*=13.73), *t(24)*=0, *p*=1, *d*=0. Similarly, the players' nausea ratings did not significantly differ between pre- (*M*=7.63, *SD*=9.54) and post-measurement times (*M*=11.45, *SD*=13.49), *t(24)*=-1.29, *p*=0.211, *d*=-0.26.

Neither the energetic nor the valence sub-scale of the MMQ showed significant differences between before and after scores of playing the game.

6.2 Post-Questionnaires

We report the descriptive values of the questionnaires administered as only post-game measures in Table 2. The findings indicate that all measures were rated with a positive tendency. Whereas most constructs highlight a highly positive experience, the PXI-mastery sub-category indicates that the players did not feel a particularly high mastery in the game.

6.3 Game Performance

For the first three levels, we logged the participants' hit ratio as the main performance measure. By adding the dynamic difficulty adaption in our game design process, we aimed for an overall success

Table 1: The table shows the descriptive and the results of statistical tests of pre-post SSQ and MMQ questionnaires (* *indicates significance*).

Questionnaires	Pre-Que. Mean	Pre-Que. SD	Post-Que. Mean	Post-Que. SD	Statistical Test	P Value	Effect Size	Confidence Interval (.95)
SSQ Total	15.41	13.41	21.09	14.76	$t(24)$=-1.71	0.100	d = -0.34	[-12.533, 1.163]
SSQ-nau.	15.26	11.02	33.58	17.44	V=4.5	<0.001*	r = -0.55	[-28.620, -14.310]
SSQ-ocu. dis.	15.77	16.80	11.82	14.19	V=72.5	0.220	r = -0.17	[-7.580, 22.740]
SSQ-dis.	6.12	12.76	7.80	13.38	V=11	0.170	r = -0.19	[-13.920, 13.920]
MMQ-ene.	3.6	1.35	4.1	1.61	$t(24)$=-1.50	0.146	d = -0.30	[-1.187, 0.187]
MMQ-val.	4.6	1.24	4.2	1.55	V=112	0.092	r = -0.24	[-0.000, 1.250]

Table 2: The player experience and physical activity enjoyment of players were generally high.

PXI-enj. Mean	PXI-enj. SD	PXI-mas. Mean	PXI-mas. SD	PXI-imm. Mean	PXI-imm. SD	PXI-pro. fee. Mean	PXI-pro. fee. SD	PXI-aud. app. Mean	PXI-aud. app. SD	PXI-cha. Mean	PXI-cha. SD	PXI-eas. Mean	PXI-eas. SD	PXI-cla. Mean	PXI-cla. SD	Paces-8 Mean	Paces-8 SD
1.95	0.79	0.93	1.19	2.03	0.75	1.6	0.88	1.33	0.98	1.71	0.80	1.99	0.84	2.2	0.93	5.44	0.91

rate between 60% and 90%. This goal was achieved for all three levels *Tap to the Beat* (M=78.4%, SD=15.8), *Hopscotch* (M=69.6%, SD=15.4), and *Obstacle Course* (M=85.1%, SD=8.6). On average, participants spent 41.77% of the time in the medium difficulty (SD=23.63), followed by the hardest difficulty (M=35.33%, SD=25.11) and the easiest difficulty (M=22.88%, SD=19.33).

The participants mainly did not improve their jump height in the final level over the five jumps. The average height remained roughly the same from 38.28cm (SD=9.12) in the first round to 37.66cm (SD=9.10) in the last execution. However, participants improved their technique score slightly over the five jumps, starting from an average rating of 71.45% (SD=17.18) and ending at 75.45% (SD=15.30).

Generally, the game advised participants for 62% of the jumps to pay attention to the correct knee movement during the landing. This criterion was followed by a too-hard landing, an issue in 26% of the cases. Lastly, the arm swing was too high for 20% of the jumps and not fully parallel for 8% of the jumps. In contrast, asynchronous feet movements during the lift-off and landing were not an issue.

6.4 Qualitative Feedback

We collected qualitative data in the form of open-ended questions. Before the analysis, the data was translated into English using DeepL Pro [34] and was checked by one of the first authors for inaccurries. After this, we used Dovetail tool to code the data [36].

One of the first authors analyzed this data using a reflexive thematic analysis approach [16, 17]. Before the analysis, the author decided on four deductive categories: *risks and benefits*, *safety and usability*, *participation*, and *improvements*. The author coded the interview data using inductive codes (e.g., "injury risk", "accessibility of exercise opportunities", "standing zone should be improved") under these categories. Following this step, they performed an affinity mapping activity and based on this, they created following themes.

Theme 1: The main advantages of JumpExTra VR are accessibility and enjoyment, however, participants also reported injury concerns. The participants mainly attributed the advantages of this game to two factors. The first factor is the accessibility of physical exercise opportunities: "*[...] you don't need to go to the gym since you can easily exercise at home*"*(**P4**)*. Secondly, they emphasized the enjoyment aspect of *JumpExTra VR*: "*More fun while exercising*"*(**P9**)*. Interestingly, one participant reported both the pros and cons of immersion in this game: "*Forgetting the real world is a disadvantage and being completely immersed in the world is an advantage*"*(**P6**)*. Another player highlighted the positive side of this game by comparing it to another commercial alternative: "*More movement for players than in other VR games like Beat Saber*"*(**P16**)*.

JumpExTra VR was found to be associated with some drawbacks. Some players reported the possibility of losing physical-world awareness while playing this game: "*A disadvantage would be that you might get too "infatuated" with the virtual world and neglect real life*"*(**P4**)*. Additionally, many participants were concerned about the potential injury risks. These were attributed to various causes, but mostly to falling: "*I found it risky to fall down*"*(**P14**)*. The risk of physical collisions were also pointed out: "*You might bump into objects in the real environment*"*(**P8**)*. Referring to the technical feedback in the last level, one participant stressed the need for similar training instructions for the more gameful levels, too, "*because, if [they] do the tasks wrong, injuries could follow*"*(**P3**)*. Keeping the balance was mentioned as an issue for a few: "*It's kinda hard to keep balance sometimes, the risk is that you can fall on the ground*"*(**P7**)*.

Theme 2: Overall JumpExTra VR did not cause serious safety and usability issues. Yet, there were some instances reported by players. Even though participants had no severe issues regarding safety and usability, a few had difficulties understanding where they were physically located: "*I couldn't remember where I was in the room*"*(**P2**)*. Some echoed the safety issues related to having accident, falling down, and losing balance. The difficulty of staying in the standing zone of *JumpExTra VR* was also noted: "*I had trouble staying within the designated play area. I got too far ahead in places, and so I couldn't get the triggers to work properly on the first play*"*(**P5**)*. Notably, the players reported on some usability problems due to the technical VR setup: first, "*Problems with sharp vision, which strained the eyes a lot*"*(**P23**)*. Second, "*Tracking did not work perfectly*"*(**P16**)*. Third, "*The cable on [their] back was disturbing*"*(**P8**)*. Nevertheless, only one participant encountered issues with the leg trackers not staying in position, and another participant had experienced usability problem due to color blindness.

Theme 3: For most players, JumpExTra VR would positively impact participation in jump training. Most participants agreed that the chance of using *JumpExTra VR* would positively affect their long-term participation in jump training. Some commented that "*it would be good for [their] fitness*"*(**P6**)*. According to one player, especially over time, one would get better at performing jumps and at the evaluated aspects, which "*increases the average jumping power and also reduces the risk of injury*"*(**P3**)*. The feedback feature of the game was particularly appreciated by some participants and mentioned as a reason for long-term use: "*My jump will probably improve through feedback*"*(**P10**)*. For a few participants, the motivating or fun nature of *JumpExTra VR* played a role: "*The design and the atmosphere is very pleasant. It would motivate me*"*(**P19**)*. In particular, one player emphasized the advantage of using games for physical exercises: "*[...] during the games you don't really notice how you practice your jumps and therefore it is not so monotonous*"*(**P24**)*.

However, some participants would not continue using *JumpExTra VR*. For a few, this was due to safety and comfort issues that can occur when jumping in VR: "*I didn't feel safe enough to jump with full power. The headset wobbled too much for that and I was afraid of not landing properly or damaging the headset.*"*(**P5**)*. Tracking imprecision was also pointed out as a reason: "*I also found the jump training segment to be too inaccurate from a tracking standpoint*"*(**P25**)*. Additionally, there were other reasons reported by the players, such as a general dislike for VR games, loss of interest after a while, or difficulties in maintaining habits.

Theme 4: Players suggest improvements for JumpExTra VR about the game world, feedback, standing zone, and varition of game levels. Overall, we received a lot of feedback for our game design. A few participants would even "*change nothing*"*(**P13**)*. Others emphasized the parts they liked the most, like "*[...] definitely keep the music and tutorials*"*(**P6**)*. Still, we received many ideas of how to improve *JumpExTra VR*. Some players proposed improvements to the game world, such as "*mak[ing] the game environment more colorful, beautiful, lively*"*(**P8**)*, and "*a more accurate virtual body would be desirable to play better*"*(**P14**)*. A few wished to have more feedback: "*What I would change is the feedback. A sound or buzzer was missing if the jump or obstacle evasion were successful or not.*"*(**P20**)*. A part of the players did not like constantly looking down in the gameplay and improving the standing zone was recommended: "*I wished for an alert once you are outside the designated play zone*"*(**P3**)*. More variety was also suggested for jump training exercises: "*Combine the three levels for more variety (tap, jump, dodge)*"*(**P10**)*.

7 DISCUSSION

The main goal of this research project was to provide playful and safe VR-based jump exergame. Therefore, we considered both prior literature and the findings of expert interviews to design *JumpExTra VR*. As the final step, we evaluated our prototype in a mixed-methods user study (N=25). In the following section, we discuss the findings by focusing on the hypothesis and research questions and provide design implications that can help researchers and practitioners to expand on full-body exertion experiences.

7.1 H1: Our exergame does not induce significant cybersickness.

Our results partially support this hypothesis, even though the players reported higher SSQ-nausea scores after playing the game. This finding supports previous research [114] showing that VR exergames can cause symptoms of cybersickness. However, we did not observe increased ratings for the remaining categories of SSQ: oculomotor disturbance, disorientation, and the total score. We suspect the increased sickness scores were due to the sweating item of SSQ. The effect of physical training on sweating has been shown in the literature [5]. Our additional SSQ analysis, excluding the sweating item, supports this assumption; the results show no significant effect between pre- and post-measurements. As suggested by [114], we also emphasize the potential overlap between cybersickness and physical activity symptoms. Our results underline that high-intensity full-body exercises can be safely performed in VR without risking discomfort.

7.2 H2: Our exergame significantly improves the players' mood.

In line with the feedback from our domain experts and literature [24], we assumed that the physical activity in our exergame would improve the players' mood. Therefore, we assessed the players' energetic arousal and valence. However, our results from the MMQ do not support our hypothesis as neither of the two subscales revealed any significant difference. We explain this outcome two-fold. In case of the energetic arousal subcategory, most players stated being physically exhausted and sweaty after playing the game. They explicitly attributed their state to two external reasons: summer heat and headset fit. Unfortunately, the study coincided with an extreme summer drought with high temperatures. Also, COVID-19 measures forced us to use easily cleanable headset foams which accumulated extra heat. Both factors added to the expected exhaustion and potentially caused players to feel tired rather than stimulated. Still, as players generally appreciated the physical challenge, we are confident that such full-body exergames can benefit the players' physical and mental well-being in the long run.

In contrast, the slight decrease in valence scores might be connected to the low scores on the PXI's mastery dimension, indicating that participants did not feel particularly good at playing the game. Due to the time constraints of the study, we could let participants try the game only once. However, such fast and timed movements are always hard when attempting them for the first time. Therefore, we speculate that players would feel more relaxed and capable with further repetitions. In turn, a feeling of success that was missing in this first run might ultimately also positively impact participants' valence.

7.3 RQ3: How do players evaluate the player experience of our exergame and its usability as a training tool?

JumpExTra VR was implemented based on prior literature and expert interviews. Therefore, we see the high ratings of PXI as a result of the detailed design process of our game. Aligning with previous studies [41, 62, 80], we show that jump-based exergames can lead to positive player experiences. With this, we also extend the results of these studies into the training realm of jumping in VR.

Overall, the players highly enjoyed playing this game and found it immersive and appealing. The high PXI progress feedback scores show that the game provided comprehensive feedback regarding players' progress. This finding is further supported with qualitative data as the players appreciated the game's feedback feature: "*feedback will probably improve my jump*" ***(P10)***. We believe that the instructions given before each level (clarity of goals), interactive tutorials (ease of control), and dynamic difficulty (challenge) are reflected in the high scores in the respective PXI sub-categories. However, players criticized the need to look down at their feet constantly. This pose is uncomfortable and could potentially lead to postural degradation. Instead, visual and audio feedback informing players upon a hit or miss could reduce the urge to check on their own movements.

Even though most players stated they would continue using *JumpExTra VR* in the long-term, they also requested visual improvements, namely a more lively world and a better-matching avatar. Also, they proposed combining the levels for more variety in gameplay. Especially this last point is vital for the long-term success of future full-body exergames. To secure retention, developers should focus on varied gameplay with high replayability. Rhythmic elements used in our game or famous titles like Beat Saber can be easily extended by adding new songs and mappings. The repetitive technical jump training in our last level bears a much greater challenge and will likely suffer from decreasing interest. Hence, it remains an open research question on how to enhance retention for advanced training routines as well.

7.4 RQ4: How do players perceive the physical activity and perform in our exergame?

Overall, all participants performed well in our exergame. In particular, our results reveal that the individual success rates for all levels are well within our anticipated window of 60% to 90%. Hence, we can assume that our dynamic difficulty adaptation worked well in aligning the exergame's challenge to the players' individual abilities. Within our sample, the participants were also able to increase their personal technique score in the final level by 5.60 % on average. In contrast, we did not see any improvements in jump height. These observations match the domain experts' feedback that muscular changes take multiple weeks, whereas technical improvements are quickly realizable. In terms of perceptual effects, the high values in the challenge sub-category of the PXI show that the participants were positively challenged without feeling overly taxed. Additionally, the PACES-8 results highlight that the participants enjoyed the physical activity in *JumpExTra VR*. Lastly, we observed improvements in the players' skills. Initially, many participants had immense difficulties with coordination, used the wrong foot, or could not follow the song's rhythm. As their performance improved throughout the course of the game, we believe that further sessions would positively influence players' body control and neuromuscular coordination.

7.5 Design Implications

Avoid the Unintended Forward Drift (UFD). In our study, the frequent tapping and jumping on the spot led to small, unnoticed forward movements that required the players to monitor their position to prevent leaving the play area. This effect is similar to the unintended positional drift (UPD) [103] that is observed for walking-in-place locomotion techniques. In an analogy, we name our observed effect unintended forward drift (UFD). Unfortunately, we do not see an easy solution except for integrating a warning and pausing the game when players leave the designated area. Forcing players to remain precisely in one spot would increase the necessary mental effort and potentially spoil the game experience. An option would be to integrate omnidirectional gameplay where players jump in all directions and not just forward. However, such game design is challenging because it adds events behind the players' backs.

Consider Technical Constraints. In our pilot tests, we experimented with different approaches to attaching the trackers to the players' legs. In the end, we decided on the shins. Compared to typical shoe adapters, trackers are more stable, more comfortable to wear, and easier to attach in this position. However, during the study, we sometimes noticed that trackers slipped slightly, especially if participants wore slick pants. Even if trackers remain in place, Vive lighthouse tracking is not accurate enough for fast leg movements despite being one of the most precise VR systems. Consequently, we noticed considerable jittering during the game. This problem is not severe in the rhythmic levels and was not noticed. However, when using the tracking data to display a replay of the vertical jump, users see this suboptimal tracking quality. Consequently, we recommend applying a slight low-pass filter to remove artifacts in cases where players see their own movements, like in our replay.

Besides visual artifacts, the tracking-related inaccuracies also influence the quality of the jump-technique feedback. Paired with a great variety of different body types and postures, these technical constraints can increase the false-positive rate of mistake detections, such as problematic knee movement. To avoid wrong corrections manifesting in the players' jump technique, automated feedback should be a tool only to support their own critical reflection on their movements. In this context, we noticed that players often did not recall what the optimal jump, shown in the tutorial, looked like and could not draw proper conclusions for their jump. Hence, we recommend tying visualizations of the "optimal performance" with the replay and complementing both with the less-precise automatic feedback. Ultimately, this combination further improves the players' critical view of their performance and may lead to lasting technical improvements.

Account for Safety Concerns in Fully-Body VR Exergames. As we have seen with the UFD, performing full-body movements in VR has safety concerns that must be accounted for early in the game design pipeline. In particular, one of the main reasons we initially chose to focus on the vertical jump is its compatibility with normal-sized tracking areas. Other movements, such as forward jumps, transport users quickly to the play space's borders or beyond. This consideration is particularly important for game developers who must account for the varying consumer play spaces that often do not have the generous size of a $16m^2$ VR lab.

Another critical concern is the potential risk when using a cable-bound VR headset, such as the Vive Pro. In our case, players mostly did not move enough in the tracking area to encounter cable-related issues. However, one of the authors was always present to monitor the participants' behavior. Of course, this approach is no solution for commercial applications. Lastly, we noticed that participants generally had more problems with balance than in real life. Since accidental tripping in smaller tracking areas could easily lead to collisions, developers should consider this observation.

Incorporate Rhythmic Elements with Fluent Movement Patterns. Similar to other successful exergames like Beat Saber, we aligned the players' movements in the first three levels to the beats of a song. This game design was widely appreciated by the participants who asked us to "*[...] definitely keep the music and tutorials*"***(P6)***. However, it is essential to limit the length of each level, as fast jumping and hopping exercises are exhausting. In our case, we used only two-minute songs. Also, we incorporated frequent "resting passages" featuring fewer and slower interactions to allow players to regain their breath.

In our game design process, we experimented with various movement patterns and learned which worked well or harmed the game experience. First, frequent switches between single-leg and double-leg movements are highly challenging and require excellent coordination and balance. Also, the rhythm of steps and jumps should be mostly regular and seldom change. For instance, patterns on every, every second, or every fourth beat work perfectly fine. However, repeated transitions between these intervals interrupt the players' flow and cause frustration due to missed notes. For single-leg tapping and hopping, we found that a "walking-like" pattern, i.e., switching the feet between every note, works well. A good equivalent for two-legged moves is repeatedly jumping into a narrow and a wide stance.

Adapt the Difficulty According to Players' Fitness Level and Improvements. Another key feature of our game is the dynamic difficulty adaptation. The application constantly monitors the players' performance and switches to another difficulty level on demand. This functionality allows us to challenge every player regardless of their fitness level and ability without overtaxing beginners. Our analysis of the game's performance measures revealed that the participants spent most of the time in the medium and hard difficulties. In contrast, the easiest difficulty was rarely used. Hence, we see potential in better balancing the difficulty levels and improving the transition parameters. However, estimating the effective difficulty of a particular song mapping is not easy. For instance, we explained in the previous design implication that fewer interactions do not automatically translate into an easy gameplay. Whereas our three difficulty levels provided an optimal challenge for most players, some felt overtaxed with the easiest difficulty. Other participants were not even challenged by the hardest level. Hence, we recommend adding more difficulty levels to fit every fitness level. Although the performance mainly depends on the players' exercise habits and body coordination, some participants described their regular gaming activities as good training for the reactive exercises.

7.6 Limitations

We used a Vive Pro headset with Vive Trackers in our study. This decision was mainly motivated by the improved tracking quality compared to alternatives, such as the Kinect. However, the use of a cable-bound system also led to usability and safety concerns. Whereas we are confident that active monitoring during the exergame prevented any dangerous situations, we accept that participants might have felt more insecure or disturbed by the VR system.

For the qualitative data in our research, we reflect on our background and potential research interests that might have impacted the analyzing process [101]. One of the first authors involved in the expert interview analysis has a computer science background and has published on VR, locomotion, and games research before. The other first author, who conducted both qualitative data analyses, has research experience in VR and exergames for varying user groups and a background in psychology and cognitive systems. Hence, they may have introduced bias into the analysis due to their interests and background. However, we also consider that the combination of these different specialties and perspectives enriches the data processing step.

8 CONCLUSION

VR exergames can provide a great motivation to pursue a more active lifestyle and exercise regularly at home. However, most available games incorporate only hand movements into their routines, which leaves the lower body, already weakened by all-day sitting, severely undertrained. In this work, we explored the potential of full-body VR exergames using the example of vertical jump training. Therefore, we interviewed nine domain experts and combined their feedback with insights from prior research into our exergame prototype *JumpExTra VR*. In the first three levels, the game trains lower body coordination, stability, and endurance, before providing technical feedback on the execution of maximal vertical jumps.

Additionally, we conducted an exploratory user study to evaluate how players perceive the training experience with *JumpExTra VR*. Our results reveal that the participants appreciated the physical challenge and enjoyed our jump-centered exergame. Based on the participants' feedback, we provided a set of design implications that can guide future work on full-body VR exergames and help developers design engaging experiences. In future work, we want to extend our research by evaluating the long-term effects of our exergame and compare the training effects of this game with supervised training.

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