DISSERTATION

Investigating the Constructs that Shape and Enhance the Experience of Virtual Reality Exergames

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Abstract

Modern virtual reality (VR) systems have an inherent physical component, as body interactions and movement through space are central components of the interaction with the system. In addition, VR systems are characterized in particular by creating a strong sense of being in a virtual environment that can benefit the player's motivation. Since a lack of motivation is one of the main reasons for physical inactivity, which is associated with numerous adverse effects, VR thus represents a promising technology for modern exergames, digital games focusing on physical movements. Based on five peer-reviewed papers, this thesis, therefore, explores different player experience-related aspects and game mechanics in the context of VR exergames. For each paper, a dedicated prototype was developed and evaluated in a quantitative user study. The first paper presents the advantages of a VR exergame compared to a conventional exergame played in front of a TV screen for presence, motivation, performance, embodiment, and attentional focus. The second paper examines that the haptic feedback provided by using a heavy passive haptic controller can significantly increase exertion in a VR exergame without reducing player motivation. The results presented in the third paper show that playing in two physically separated rooms in a two-player VR game significantly improves social presence, performance, and the quality of communication compared to playing in a shared playing area. For the fourth work, a unique controller based on a grip strength trainer was developed to enable a strenuous voluntary interaction. Different game mechanics were integrated into a VR game to incentivize engaging in the voluntary interaction. The results show that the exaggerated representation of one's abilities, called virtual performance augmentation, is the strongest motivator for voluntarily engaging in the strenuous activity. On the one hand, the fifth paper investigates the influence of VR for exergames in the context of cognitive performance and, on the other hand, analogous to the first paper, the influence on presence, motivation, and perceived exertion. While no benefits for VR were identified for cognitive performance, the results of this work support the findings from the first work and demonstrate the benefits of VR for presence, motivation, and perceived exertion for exergames. Incorporating the results of all work, the discussion of this thesis presents and discusses findings relevant to future research and the development of VR exergames. This dissertation demonstrates that VR technology and related mechanics can significantly enhance exergames and thus contribute to tackling the problem of physical inactivity in a motivating way.

Kurzzusammenfassung

Moderne Virtual Reality (VR) Systeme besitzen eine inhärente Bewegungskomponente, da Körperinteraktionen und Bewegungen durch den Raum zentrale Bestandteile der Interaktionen mit dem System darstellen. Darüber hinaus sind VR-Systeme insbesondere dadurch charakterisiert, dass sie ein starkes Gefühl dafür vermitteln, sich in einer virtuellen Umgebung zu befinden, was sich positiv auf die Motivation der Nutzer auswirken kann. Da Motivationsmangel einer der Hauptgründe für körperliche Inaktivität ist, die mit zahlreichen negativen Auswirkungen verbunden ist, stellt VR eine vielversprechende Technologie für moderne digitale Spiele dar, die sich auf körperliche Bewegungen konzentrieren und als Exergames bezeichnet werden. Auf der Grundlage von fünf begutachteten Arbeiten werden in dieser Dissertation daher verschiedene Aspekte der Spielerfahrung und Spielmechaniken im Kontext von VR-Exergames untersucht. Für jede Arbeit wurde ein eigener Prototyp entwickelt und in einer quantitativen Nutzerstudie evaluiert. In der ersten Arbeit werden die Vorteile eines VR-Exergames gegenüber einem konventionellen Exergame, welches vor einem TV-Bildschirm gespielt wird für die Präsenz, Motivation, Leistung, Embodiment und Aufmerksamkeitsfokus dargestellt. In der zweiten Arbeit wird herausgearbeitet, dass das haptische Feedback, das durch die Nutzung eines passiv haptischen schweren Controllers entsteht, dazu genutzt werden kann, die körperliche Anstrengung in einem VR-Exergame signifikant zu steigern, ohne dabei die Motivation der Spieler*innen zu reduzieren. Die Ergebnisse der dritten Arbeit zeigen, dass in einem Zwei-Spieler*innen VR-Spiel, das Spielen in zwei voneinander getrennten Räumen im Vergleich zu dem Spielen in einem geteilten Raum bzw. einer geteilten Spielfläche die soziale Präsenz, die Performance und die Qualität der Kommunikation signifikant verbessert. Für die vierte Arbeit wurde ein spezieller Controller entwickelt, der auf einem Griffkrafttrainer basiert und eine freiwillige anstrengende Interaktion ermöglicht. Zur Motivation diese Anstrengung aufzusuchen, wurden verschiedene Spielmechaniken in ein VR-Spiel integriert und miteinander verglichen. Die Ergebnisse zeigen, dass die übertriebene Darstellung der eigenen Fähigkeiten, die sogenannte Virtual Performance Augmentation, den stärksten Motivator für das freiwillige Aufsuchen der anstrengenden Tätigkeit darstellt. Die Ergebnisse der fünften Arbeit unterstützen die Erkenntnisse aus der ersten Arbeit und zeigen den Mehrwert von VR für die Präsenz, Motivation und die wahrgenommene Anstrengung für Exergames. Darüber hinaus zeigt eine Untersuchung der kognitiven Leistungsfähigkeit jedoch keinen Vorteil für VR in Exergames auf. Die Ergebnisse aller Arbeiten einbeziehend, werden in der Diskussion dieser Arbeit Erkenntnisse präsentiert und diskutiert, die für die zukünftige Forschung sowie die Entwicklung von VR-Exergames relevant sind. Diese Dissertation zeigt, dass die VR-Technologie und damit in Zusammenhang stehende Mechaniken Exergames signifikant verbessern können und so dazu beitragen können, das Problem der körperlichen Inaktivität auf motivierende Weise anzugehen.

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List of Publications

The following list contains all publications I was involved in during my doctoral studies. This list is divided into two parts. The first part contains all papers on which this dissertation is based and that are attached at the end of this dissertation. The second part lists the publications I was involved in but which are not part of this dissertation.

[1] **Born, F.**, Abramowski, S., & Masuch, M. (2019, September). Exergaming in VR: The Impact of Immersive Embodiment on Motivation, Performance, and Perceived Exertion. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)* (pp. 1–8). IEEE. DOI: 10.1109/VS-Games.2019.8864579

[2] **Born, F.**, Masuch, M., & Hahn, A. (2020, August). Ghost Sweeper: Using a Heavy Passive Haptic Controller to Enhance a Room-Scale VR Exergame. (Best Paper Nomination) In *2020 IEEE Conference on Games (CoG)* (pp. 221–228). IEEE. DOI: 10.1109/CoG47356.2020.9231867

[3] **Born, F**., Sykownik, P., & Masuch, M. (2019, August). Co-Located vs. Remote Gameplay: The Role of Physical Co-Presence in Multiplayer Room-Scale VR. In *2019 IEEE Conference on Games (CoG)* (pp. 1–8). IEEE. DOI: 10.1109/CIG.2019.8848001

[4] **Born, F.**, Rygula, A., & Masuch, M. (2021, September). Motivating Players to Perform an Optional Strenuous Activity in a Virtual Reality Exergame Using Virtual Performance Augmentation. In *Proceedings of the ACM on Human-Computer Interaction, 5.* CHI PLAY (2021). (pp. 1–21). DOI: 10.1145/3474652

[5] **Born, F.**, Graf, L., & Masuch, M. (2021, August). Exergaming: The Impact of Virtual Reality on Cognitive Performance and Player Experience. (Best Paper Nomination) In *2021 IEEE Conference on Games (CoG)* (pp. 1–8). IEEE. DOI: 10.1109/CoG52621.2021.9619105

Further Publications

[6] **Born, F.**, & Masuch, M. (2017, September). Masking Distracting Ambient Sound in an Adaptive VR-Application to Increase Presence. In *International Conference on Entertainment Computing* (pp. 226–232). Springer, Cham. DOI: 10.1007/978-3-319-66715-7_25

[7] **Born, F**., & Masuch, M. (2017, December). Increasing Presence in a Mixed Reality Application by Integrating a Real Time Tracked Full Body Representation. In *International Conference on Advances in Computer Entertainment* (pp. 46–60). Springer, Cham. DOI: 10.1007/978-3-319-76270-8_4

[8] Sykownik, P., **Born, F**., & Masuch, M. (2019, August). Can You Hear the Player Experience? A Pipeline for Automated Sentiment Analysis of Player Speech. In *2019 IEEE Conference on Games (CoG)* (pp. 1–4). IEEE. DOI: 10.1109/CIG.2019.8848096

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Acronyms

%HR	Percentage of the Maximum Heart Rate
%HRR	Heart Rate Reserve
CAVE	Cave Automatic Virtual Environment
DDR	Dance Dance Revolution
HMD	Head-Mounted Display
HR	Heart Rate
HR_{max}	Maximum Heart Rate
HR_{rest}	Resting Heart Rate
Hz	Hertz
IMI	Intrinsic Motivation Inventory
IPQ	Igroup Presence Questionnaire
PX	Player Experience
RQ	Research Question
SDT	Self-Determination Theory
SSQ	Simulator Sickness Questionnaire
VPA	Virtual Performance Augmentation
VR	Virtual Reality
WHO	World Health Organization

Chapter 1

Introduction

In 2018, the World Health Organization (WHO) launched the Global Action Plan on Physical Activity [Org18] that has set the goal to reduce physical inactivity of adolescents and adults by 15% by 2030. The main reason for this long-term plan relates to the problem that on average, 27.5% of adults aged 18 years and older [Gut+18] and more than 81% of adolescents aged 11 – 17 years [Gut+20] worldwide do not meet the global recommendations on physical activity for health of the WHO guidelines [Org10]. These guidelines recommend 150 – 300 minutes of physical activity in moderate intensity or 75 – 150 minutes in vigorous intensity per week for adults and one hour each day of moderate to vigorous intensity for children. Physical inactivity is responsible for a total of 9% of premature mortality. Compliance with the guidelines would mean an increase in the average life expectancy of the entire world population of 0.68 years [Lee+12]. Further, physical activity is associated with various physical [Sat+11; LFB03; LBC05; WSE05] and cognitive [Sax+05; RM07] benefits. Against the background of these figures, the high proportions of adults and children not meeting the WHO guidelines appear alarming. At the same time, however, this fact also raises the question of why such a large proportion of the population does not engage in regular physical activity. Information on the individual motives for physical inactivity among the German population is provided by the results of the 2016 physical activity study conducted by the Techniker Krankenkasse [Kra16]. The main reasons given by the physically inactive persons asked in the report, with the option of multiple responses, were too long distances to engage in physical activity (47%), lack of time (45%), physical limitations and impairments (28%), and lack of motivation (28%). However, it can be seen that a lack of motivation has a major influence on the two main reasons mentioned for physical inactivity, as it can be assumed that long distances and time are invested for other activities. Physical activity alone (independent from the place where it is performed) does not seem to induce enough motivation. Similarly, it does not induce enough motivation to invest time by reducing engagement in other activities. So motivation is inherently integrated into most of the reasons presented in the survey. Thus, physical activities' motivational appeal is not high enough to engage in them.

Beyond the problem of physical inactivity, also engaging in sedentary behavior is associated with severe risks. Sedentary behavior is not only to be understood as the absence of moderate-to-vigorous physical activity but represents a separate behavioral category that comes with its own risks [Owe+10; Tre+07]. Sedentary behavior can be defined as extended periods of sitting during work-related or private activities such as working, watching TV, gaming, or driving a car [Owe+10]. On average, the time adults, children, and adolescents engage in sedentary behavior per day is about 8 hours [Bau+18]. Daily sedentary behavior that exceeds 7.6 hours a day is linked to a considerably higher risk of dying from all causes [Cha+13], independent from the amount of physical activity [Kat+09]. Hence, increasing physical activity should be coupled with a reduction in sedentary behavior. To address the problem of physical inactivity and sedentary behavior to the same extent, a measure is needed that replaces sedentary behavior with physical activity while considering the lack of motivation as one of the main reasons for physical inactivity.

A sedentary activity with a high motivational potential for many is playing digital games. In Germany in 2020, 34.3 million people played digital games on smartphones, PCs, or consoles [GBe20]. The average age of gamers has been rising steadily and was 37.5 years in 2020. The gender ratio is quite balanced, with 48% female gamers and 52% male gamers. Beyond that, a survey from 2020 with 4500 participants from 14 countries shows that players of digital games across all age groups play digital games on average more than 6 hours per week, and even players over 60 years play 4.7 hours per week on average [Net20]. Hence, since a large part of the population plays digital games voluntarily and regularly, it can be derived that digital games have a tremendous motivational appeal to many individuals. Digital games have an inherent psychological appeal as they contribute to the satisfaction of the basic needs of competence, autonomy, and relatedness [RRP06]. According to the Self-Determination Theory (SDT) proposed by Ryan and Deci [RD00a], intrinsic motivation arises from the satisfaction of these three basic needs, which in turn drives the voluntary pursuit, and the enjoyment of a particular activity [Rya+09]. Digital games have become an integral part of leisure activities and are the epitome of sedentary behavior, as they are usually played while sitting in front of a screen. Also, for adult males, the duration of digital gaming is negatively correlated with the frequency of exercise and positively correlated with body mass index [Bal+09]. Hence, if the inherent sedentary behavior of digital games could be changed and replaced with physical activity, several problems would be solved simultaneously. The physical activity required by the game could contribute to the amount of physical activity recommended by the WHO, and the players would engage in less sedentary behavior. Even short intervals of physical activity are beneficial and count towards the total amount of suggested physical activity because, according to the WHO, it is irrelevant how many individual units the total physical activity consists of [Bul+20]. Embedding physical activity in digital games would also offer significant benefits in terms of the individual motives of physically inactive people. On the one hand, there would be no distances to travel to engage in physical activity. On the other hand, the high motivational potential of digital games could compensate for the lack of motivation as one of the main reasons for physical inactivity.

Digital games that embed physical activity into the gameplay are called exertion games or exergames. Famous examples of exergaming systems and games include Microsoft's Kinect, Sony's Eye Toy, Nintendo's Wii Fit [EAD07] and Sports [EAD06], Dance Dance Revolution [KB98], and Nintendo's Ring Fit Adventure [Dev19], which was recently released in 2019 and has since sold more than 11 million copies [NC21]. By combining the motivational nature of digital games with physical movement, exergames have been used in a wide variety of different areas such as supporting physical rehabilitation and physical activity for older adults [KMBN19], preventing and counteracting childhood obesity [GC14], improving cognitive performance [GM12; AH+12], improving self-concept, as well as psychological and social well-being [JAS17], and as motivators to perform physical activities in general [Gao+15].

With the introduction of modern room-scale virtual reality (VR) systems like the HTC Vive or Oculus Quest, exergaming became a fundamental interaction paradigm as VR games naturally require players to stand, walk and interact with the game using their entire body. Room-scale VR systems allow players to move in a fixed, defined area within the physical space. By tracking the player's exact head position and movements, the player's movements in the real world are transferred to the virtual world. Most room-scale VR systems incorporate special controllers that allow a direct mapping of the player's hand positions and movements in the real world to their virtual representations. Room-scale VR and corresponding games for this technology thus break through the inherent sedentary behavior associated with digital games. Due to the required body movements for interaction with the virtual environment, room-scale VR systems even have an inherent exergaming property, which can be more or less prominent depending on the required movements of the game. In addition to the inherent physical component of VR room-scale technology, VR also offers the advantage of high immersion compared to conventional digital games played in front of a screen. Immersion can be understood as an objective characteristic of a technical system that describes the degree to which the user is integrated into a virtual environment [Sla09]. By using modern head-mounted displays (HMD), the player's real-world is hidden, and only the virtual one is presented. Head movements, as in the real world, lead to a matching change of the view in the virtual world. The result is a much more real three-dimensional impression of the world than possible in front of a conventional screen. This highly immersive feature of VR technology can have a substantial impact on the player's sense of actually being in the virtual world [SU94]. This construct, described as presence [Hee92], is central when it comes to the experience of virtual worlds, among other reasons because in digital games, presence has a significant impact on the satisfaction of the psychological needs proposed by the SDT and thus can have a substantial impact on the player's motivation [RRP06]. The use of VR room-scale technology is thus predestined to break the sedentary behavior associated with digital games and further can potentially enhance the motivational appeal of digital games due to the highly immersive nature of the technology.

1.1 Research Questions and Main Contributions

Since VR has only been in widespread use for a few years, and technological advances and lower prices have favored access and everyday use of the technology, the effective design of VR exergames is a young discipline. Fundamental questions remain about how individual aspects of game design, or technical components, affect player experience. In the context of the idea that room-scale VR games have an inherent exergaming property and can provide additional motivational value over non-VR games due to their also inherent highly immersive nature, this dissertation examines five different research questions (RQ) based on the papers which will be presented in the Chapters 3 – 7. All research questions investigate how different VR applications and settings affect constructs that are vital in the context of exergaming. Four of the five papers, presented in the Chapters 3, 4, 6, and 7 directly examine questions in the context of exergames and consider the effects of VR or different VR settings on relevant constructs such as presence, motivation, or exertion (RQ 1, 2, 4, 5). Another paper (RQ 3) which will be presented in Chapter 5 examines social presence in a room-scale VR game, which is an important construct in the context of exergames. The research questions of each paper are presented in the following, along with an overview of the dissertation's contribution as a result of answering the research questions.

RQ 1: Can VR enhance the player experience of exergames? Which impact do the output device, the perspective, and the tracking fidelity have? (Chapter 3; [BAM19])

RQ 2: How can the exertion in a VR exergame be increased without reducing the motivation? (Chapter 4; [BMH20])

RQ 3: What impact does physical co-presence in a multiplayer room-scale VR game have on the player experience? (Chapter 5; [BSM19])

RQ 4: Can players of a VR exergame be motivated to engage voluntarily in an optional strenuous activity? (Chapter 6; [BRM21])

RQ 5: What impact does VR have on cognitive performance and player experience in the context of an exergame? (Chapter 7; [BGM21])

For each of the five research questions, a dedicated VR game was conceptualized, implemented, and evaluated with a quantitative user study. By answering the research questions above, it will be elaborated that VR offers a significant benefit for players in the context of exergames. Of particular importance are the advantages of VR for the player's presence, embodiment, motivation, and perceived exertion. Furthermore, it is shown that the increase of exertion in exergames does not necessarily have to be accompanied by a loss of motivation. Suitable mechanisms are presented that can compensate for the loss of motivation or even serve as an incentive to engage in an optional strenuous activity voluntarily. Furthermore, it is shown that two play areas physically separated from each other significantly increase social presence and performance in a multiplayer room-scale VR game compared to players playing in the same play area. Further, it will be shown that besides the benefits VR has in the context of exergames, there are also areas like cognitive performance that do not benefit from a VR system. With the answers to the research questions and the findings obtained, this dissertation contributes to the field of VR exergaming research on the one hand and serves as a guideline catalog that can be used for the future development of highly motivational VR room-scale (exer)games on the other hand.

1.2 Structure of the Dissertation

This dissertation consists of two parts. The first part is the synopsis (Chapter 1 – 8) and the second part forms a collection of five published papers given in the *List of Publications*. The synopsis embeds the publications in the overall context of VR exergames and underlying constructs and discusses the findings of all papers in this context. In the next chapter, the briefly outlined topics of the introduction and the constructs important for this synopsis will be presented in more detail, and existing preliminary work and its results will be presented. This theoretical background chapter is followed by five chapters in which the five publications are presented. Each publication is first introduced, embedded into the theoretical background, and then presented in a summarized form. However, no specific details such as p-values, mean values, or effect sizes are presented in this synopsis. These details are part of the attached papers. Instead, this synopsis summarizes each paper, outlining its approach, development, evaluation, and critical findings. Furthermore, the summary is entirely descriptive and does not include a discussion or conclusion since these are part of the respective publications. The discussion of the results of all papers in the context of the research questions and the underlying subject of this dissertation is presented in the discussion chapter. Contributions are identified and discussed based on the results of the individual papers and in the context of existing research and concerning future research and developments.

Chapter 2

Theoretical Background

This chapter covers the theoretical background of the topics and concepts relevant to this dissertation. In order to elaborate on the main reason for physical inactivity and the appeal of digital games, the concept of motivation will first be explained in more detail and related to physical activity and digital games. After that, exergames and their effects are defined precisely, especially in the motivation framework explained before. Next, a summary is given on the areas in which exergames have already been used and what beneficial value exergames can have, especially in comparison to conventional physical activities. Subsequently, the constructs immersion and presence are presented, followed by the topic of (room-scale) VR games and findings on the influence of VR on central exergaming constructs.

2.1 Motivation

What determines the action or lack of action of a person? In everyday life as well as in science, the concept of motivation exists to answer this question. Motivation can be defined as the entirety of all motives and their interaction with situational incentives [MBR16]. In this context, motivation influences the choice of a particular behavior to achieve a goal as well as the persistence, intensity, and direction of the action [MBR16]. Motivation thus determines whether an activity such as engaging in sports or playing digital games is performed. However, the emergence of motivation in the process is a highly complex and much discussed and studied process. There are numerous models and theoretical approaches that explain the emergence of motivation [GW96]. The presentation and differentiation of these various models would go beyond the scope of this dissertation. Instead, one of the most prominent motivation theories, the SDT proposed by Ryan and Deci [RD00a], will be presented in the following. Due to the popularity of the explanatory approach, this theory has already been applied to and studied in a variety of different domains, such as physical activities [Rya+09] and digital games [RRP06].

The SDT consists of six mini-theories to explain a broad spectrum of different motivation-based phenomena. The detailed description and differentiation of all mini-theories exceed the scope of this dissertation. Instead, an overview of the most

Behaviour	Nonself-Determined					Self-Determined
Motivation	Amotivation	Extrinsic Motivation				Intrinsic Motivation
Regulatory Styles	Non-Regulation	External Regulation	Introjected Regulation	Identified Regulation	Integrated Regulation	Intrinsic Regulation
Perceived Locus of Causality	Impersonal	External	Somewhat External	Somewhat Internal	Internal	Internal
Relevant Regulatory Processes	Nonintentional, Nonvaluing, Incompetence, Lack of Control	Compliance, External Rewards and Punishments	Self-control, Ego-Involvement, Internal Rewards and Punishments	Personal Importance, Conscious Valuing	Congruence, Awareness, Synthesis With Self	Interest, Enjoyment, Inherent Satisfaction

FIGURE 2.1: The Self-Determination Continuum based on the SDT by Ryan and Deci [RD00a]

relevant aspects of the entire SDT in the context of this dissertation is given here. One of the most important distinctions made in SDT is the division of motivation into intrinsic, extrinsic, and amotivation. Intrinsic motivation describes the motivation to engage in an activity because of its inherent satisfaction. Engaging in the activity itself is characterized by the fact that it is perceived as interesting, enjoyable, and satisfying without external incentives, rewards, or punishments. Amotivation describes the absence of motivation to perform a particular activity and is the diametric opposite of intrinsic motivation. Between intrinsic motivation and amotivation is extrinsic motivation. According to the authors of the SDT [RD00a], engaging in activities for the sole reason of interest or gratification is rarely found in reality, especially in adulthood. In particular, everyday obligations and social pressures provide external incentives to engage in an activity that has inherent satisfaction for a minority of individuals. Extrinsic motivation thus describes the motivation to engage in an activity due to external incentives and is thus opposed to intrinsic motivation [RD00a]. However, this fact leads to why extrinsic motivators for a particular activity can lead to the activity being performed with personal commitment and even being perceived as enjoyable. The better a requested behavior can be integrated into one's sense of self, the more likely this behavior will be internalized, and the more intrinsically motivating the action is perceived. According to the SDT, there are different degrees of internalization of an externally requested behavior. Hence, a self-determination continuum was created to explain these characteristics, which is illustrated in Figure 2.1. On the right side of the continuum is intrinsic motivation, which leads to self-determined behavior. On the left side of the continuum is amotivation, which describes a non-self-determined behavior. Between these two extremes of motivation lies extrinsic motivation. Extrinsically motivated behavior is divided into four subcategories on this continuum in terms of the degree of autonomy of regulation [RD00a].

The behavior due to an extrinsic motivator with the lowest degree of autonomy is the *externally regulated* behavior that is performed to satisfy an external demand, to obtain a possible reward, or to escape a potential punishment. The behavior is perceived as alienated and controlled. *Introjected regulated* behavior refers to behavior that has a higher degree of autonomy than externally regulated behavior, but the regulation of the behavior is not accepted as one's own. Introjected regulated behaviors are performed to strengthen the ego or to avoid anxiety or guilt. *Identified regulate*d behavior occurs when the desired action is perceived as personally essential, and one can identify with the goals of the actions. *Integrated regulated* behavior describes the most autonomous form of extrinsically motivated action. This regulation occurs when the desired action corresponds to one's self-concept, values, and needs. This form of extrinsic motivation is closest to intrinsic motivation but still counts as extrinsic motivation because the action is performed not because of the inherent enjoyment of the action but because a specific goal is being pursued [RD00a].

The more an extrinsically motivated behavior can be internalized and aligned with one's sense of self, the more it resembles an intrinsically motivated one. However, this leads to the question of which factors are decisive for this internalization. According to the SDT, there are three basic psychological needs, which, if satisfied, foster health and well-being [RD00a]. These three needs are autonomy, competence, and relatedness. *Autonomy* describes the desire of persons to organize their own behavior and that the behavior to be performed is in accordance with their own integrated sense of self [DR00]. Autonomy does not mean that persons have to be independent of other persons. Autonomy arises primarily through a perceived sense of choice within an activity, even if this activity has to be carried out due to dependence on other persons [SDR09]. *Competence* describes the need to control the outcome of an action and to experience mastery [Whi59]. *Relatedness* describes the need to be connected with others, to care for others, and to be cared for by others [DR00; BL95]. The satisfaction of these three basic needs has a strong influence on how strongly an externally motivated action can be internalized and thus be considered more self-determined [RD00a]. In this context, the three basic needs are considered universal and independent of culture. However, the degree to which the needs have to be satisfied is individual and depends strongly on the cultural context [DR00]. Furthermore, the satisfaction of these three basic needs is also essential in the context of intrinsic motivation. Initiating an activity due to intrinsic motivation is given by the inherent interest of that activity. However, the maintenance of this activity is determined by the degree of satisfaction of the three basic needs while engaging in the activity [DR00]. For example, if an activity is performed due to high intrinsic motivation, but the performance of the activity is then linked to an extrinsic incentive such as a reward or threat, the person's autonomy is reduced, and their intrinsic motivation is undermined [RD00a; DKR99]. However, if an extrinsic incentive is used, which has a more internal perceived locus of causality, such as positive feedback, a person's autonomy, and thus intrinsic motivation can be increased [RD00a; DKR99].

2.2 Physical Activity and Motivation

Lack of motivation was a reported primary reason for inactivity among those who were physically inactive. Physical activity can be defined as "any bodily movement produced by skeletal muscles that results in energy expenditure" [CPC85, p. 126]. Activities in the moderate-intensity range include walking at a speed of 5 – 6.5 km/h, mowing the lawn, slow dancing, or cleaning windows. Activities in the vigorous-intensity range include a wide range of sports such as jogging at 8 km/h, soccer, tennis, or basketball, as well as everyday activities such as carrying heavy loads or shoveling sand [SM+13]. Concerning the lack of motivation as a primary reason for physical inactivity, why are there such significant differences in the context of physical activity within the population? While physical activity is a fundamental part of everyday life for large numbers of people, for many others, it represents an almost insurmountable aversive stimulus, although a large number of different benefits are associated with physical activity. In order to explain this phenomenon and offer ways to improve individual motivation to engage in physical activity, physical activity has often been considered and analyzed in the context of SDT [Tei+12].

Engaging in physical activities can be fundamentally divided into intrinsic and extrinsic reasons [Rya+09]. A physical activity may be pursued because of the intrinsic interest that accompanies it or because of extrinsic factors such as mandatory physical education at school or improving health and appearance. Often, intrinsic motivation for a particular physical activity is accompanied by extrinsic added value [Rya+09]. The more these external factors can be aligned with one's own sense of self, the better they are internalized, and the more autonomous and self-determined is the performance of the physical activity. The more the basic needs for autonomy, relatedness, and competence are satisfied, the more the emergence of intrinsic motivation is supported and the more the physical activity is enjoyed and the more persistently it is performed [Rya+09; Tei+12].

The degree to which autonomy can be satisfied depends strongly on the context of the physical activity. While individual activities such as jogging can be done without restricting others or potential undermining rewards or punishments, this is less the case in the context of team or even non-voluntary school sports. In these contexts, autonomy support from others such as coaches, teachers, parents, or teammates is vital to increase autonomy, and thus intrinsic motivation [Hag+09; Spr+06], vitality [ADN08], and performance [Spr+06]. Fundamentally, to support autonomy, it is essential to provide a meaningful rationale, acknowledge the behaver's perspective, and covey choice rather than control [Dec+94]. The use of incentives to reward and motivate in the context of physical activity and autonomy is ambivalent. On the one hand, incentives such as awards or prizes can have the effect of undermining the autonomy of individuals with high intrinsic motivation [OM78; Che+20], thereby reducing their motivation to engage in the physical activity. On the other hand, incentives such as financial rewards for short periods (4 – 26 weeks) can lead individuals to engage in physical activity more frequently [Mit+13], even for short periods (16 weeks) after receiving the financial reward [CG09]. However, even though rewards may provide a short-term incentive to engage in physical activity, in the long run, they undermine a person's autonomy and thus intrinsic motivation [RD00b].

Perceived competence in the context of physical activity is based on a person experiencing a certain level of confidence and effectiveness [Rya+09] and describes the perception of a person's ability in a specific context [Fai03]. The information on how persons assess their competence depends on the environment and peers [Fai03]. Three things, in particular, are essential in the facilitation of perceived competence in the context of physical activities: optimal challenge [RD00a], motor skill competence [Sto+08], and positive feedback of others [Rya+09]. The optimal challenge describes a challenge that is in line with a person's skills. According to the SDT, a match between a particular challenge and a person's skill to solve this particular challenge leads to the person experiencing competence. The idea of the optimal challenge is not only described in the SDT but also part of other motivation theories, such as the Theory of Flow [Csi90] or the Competence Motivation Theory [Har78]. Especially the Theory of Flow describes the fit of skill and challenge in detail. According to this theory, when challenge and skill are balanced, a flow experience occurs, perceived as intrinsically rewarding and enjoying and characterized by an intense focus on the task, a sense of personal control over the situation, and a distortion of the temporal experience of the activity. This state is similar to that of intrinsic motivation from SDT. Kawabata and Mallett [KM11] observed that about 56% of people who exercise regularly experience flow when performing a physical activity. However, flow can even be elicited in physically inactive individuals in several different physical activities such as running, playing soccer, or strength training, if the corresponding activity is adapted to the skills of the inactive individuals [Elb+10]. If the skills exceed the challenge, boredom may result. If the challenge exceeds the skills, anxiety may result. An imbalanced situation may lead to the withdrawal from the activity [Csi00; Csi90].

Motor skills include all the necessary basic skills such as jumping, throwing, aiming, kicking to perform physical activities. According to Stodden and colleagues [Sto+08], the perception of motor skill competence is related to performing physical activity. The lower the perceived competence, the less a person engages in physical activity. The lower engagement in physical activity, in turn, further reduces perceived competence, and a downward spiral is initiated. When physical activity is performed with others, feedback from others such as teammates, coaches, or parents is particularly relevant [Rya+09]. Criticism and negative feedback lead to a reduction in perceived competence, while meaningful positive feedback can lead to an increase in the experience of competence [Rya+09]. Thus, to increase a person's perceived competence in the context of physical activity, it is vital that the person experiences competence. This can happen through an optimal challenge that considers a person's skills, a positive perception of motor skill competence, or through positive feedback from other people involved.

Relatedness as a third basic need is generated in the context of physical activity by the mediation of care, warmth, and involvement by others [Rya+09]. To satisfy this need, a social context is necessary when performing a physical activity. This can be provided in particular by team sports, but also by the social setting of a gym or the simultaneous performance of individual sports such as jogging [OM07]. The influence and significance of social settings in the context of physical activity is the subject of numerous studies [MW+18; Plu+19; All03; Nie+14], the results of which underline the importance of the social experience and thus the relatedness factor in the context of physical activity. However, even though perceived relatedness influences motivation in the context of physical activity, specific factors that promote it are rarely found in studies published so far. One exception is the work of McDonough [McD06], who found four different influencing factors for relatedness in dragon boaters. The author observed that peer acceptance, amount of social support, positive friendship quality, and the social support network size predicted the relatedness.

The relationship of STD constructs on motivation in the context of physical activity was investigated by Teixeira and colleagues [Tei+12] in their systematic review based on 66 studies that collected STD relevant variables in the context of physical activity. Regarding the three basic needs, the review concludes that especially the experience of competence by providing optimal challenge and informative feedback has a strong influence on exercise-related outcomes. Satisfying the need for autonomy shows mixed results concerning exercise-related outcomes. Half of the studies show either a positive or null association. However, no negative association was found. Regarding the satisfaction of the need for relatedness, also no negative association was found. However, according to the authors, there are either too few studies in which relatedness was an issue, or in the studies that surveyed relatedness, the measurement methods were too inconsistent, so that no positive influence of relatedness on the performance of physical activity was found. Beyond that, however, the authors conclude that there is good evidence for SDT as an explanatory approach in the context of physical activity. The authors were able to find a relationship between the degree of autonomy regulation of the physical activity and the participation in the physical activity. The authors conclude that intrinsic motivation and the associated experience of interest, enjoyment, and satisfaction are crucial for longer-term exercise participation. With regard to the large number of people who are physically inactive and also concerning the aforementioned main motives of those who are physically inactive, it can thus be assumed that performing physical activities often does not satisfy the basic needs for autonomy, competence, and relatedness enough to experience enjoyment and thus to engage in them regularly.

2.2.1 Measuring Motivation

Intrinsic motivation and the associated experience of interest, enjoyment, and satisfaction, as described in the previous section, are vital when it comes to engaging in and maintaining a particular activity such as physical activities. In order to be able to measure intrinsic motivation for a particular action in laboratory settings, the Intrinsic Motivation Inventory (IMI) [DR03] in particular has become established in studies that consider motivation. This questionnaire consists of the following seven subscales: *Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, Perceived Choice, Value/Usefulness*, and *Relatedness*.

The Interest/Enjoyment subscale is the most relevant of the seven subscales because it can be understood as a self-report measure of intrinsic motivation, according to the authors. Even though the development of intrinsic motivation is a complex process, this subscale provides a simple self-report measure of the degree of intrinsic motivation for a particular action. The remaining subscales of the IMI, such as the Value/Usefulness, Effort, or Relatedness subscales, are relevant depending on the study setting and hypotheses. The Perceived Competence and Perceived Choice subscales are positive predictors, and the Pressure/Tension subscale is considered a negative predictor of intrinsic motivation. All items and subscales of the IMI range from 1 – 7 (1 = not at all true, 7 = very true). In the context of the related work presented in the following subsections and the papers presented in Chapters 3 – 7, which form the core of this dissertation, intrinsic motivation is assessed by the IMI and especially by the Interest/Enjoyment subscale, if not stated otherwise. Thus, in the following sections and chapters, if a person's enjoyment is reported in relation to a particular activity, it represents their level of intrinsic motivation for this activity.

2.3 Digital Games and Motivation

Based on the explanation for the significance of intrinsic motivation from Section 2.2 and concerning the problem of physical inactivity mentioned in the introduction, it can therefore be concluded that many people have a lack of intrinsic motivation that prevents their long-term engagement in physical activities. Although external incentives of various kinds are suitable for providing a short-term incentive for physical activity, the long-term engagement in physical activity is determined by intrinsic motivation and the enjoyment and interest felt when performing this activity. Thus, to empower sustainable change in the context of physical inactivity, it is vital to facilitate the individuals' experience of enjoyment in performing physical activity, especially for individuals who have no or little intrinsic motivation to engage in physical activities. One way to accomplish this would be to combine an activity with a high intrinsic motivational potential with physical activity. Digital games provide an excellent foundation for this endeavor. Digital games have become an integral part of leisure activities for a large part of the population. This fact leads to the assumption that digital games have an inherent motivational characteristic that leads people of all ages to play them regularly. However, the question arises why playing digital games is so motivating to many individuals that it is voluntarily pursued over a long period. To answer this question in the context of the SDT, Ryan and colleagues conducted four different studies in their influential paper [RRP06] to identify the factors that explain the *"motivational pull"* of digital games. The authors observed that digital games can satisfy the three basic needs for autonomy, competence, and relatedness to a significant degree and thus possess a high inherent motivational potential. They also found that players' enjoyment and preference to continue playing the game in the future depend significantly on the satisfaction of the three basic needs [RRP06]. According to the authors, digital games can create a high degree of autonomy by giving the player the freedom to control what happens within a digital game [RRP06]. Even though the control options vary significantly between different digital games, digital games are always interactive and, unlike books or movies, allow players to control the action themselves. Even though player autonomy is generally high in digital games, as playing a digital game is primarily voluntary, the freedom of choice offered by the digital game is essential for maintaining autonomy when playing.

Furthermore, the authors assume that digital games have a particular influence on the experience of competence. Digital games make it possible to learn new skills intuitively and to master them. Positive feedback through mechanisms such as points or levels is a central component in digital games. In addition, digital games can offer an optimal challenge. This results from the fact that the challenges within a digital game are usually relatively easy to master at the beginning and become increasingly complex as the game progresses, thus adapting to the player's abilities. Furthermore, most digital games can even be adapted ad-hoc to the player's abilities through different self-selectable difficulty levels. Also, beyond the studies of Ryan and colleagues, challenge was evaluated as one of the most important influencing factors for enjoyment in games [Mek+14], which is furthermore moderated by the motives [SHS11] and skills of the players [AC12; Jin12]. An optimal challenge as a central motivational factor of games is often considered in the context of digital games in the Theory of Flow [Mek+14] which was introduced in Section 2.2. Flow and enjoyment are often used synonymously in this context [Mek+14; Jin11]. A fundamental concept of the Theory of Flow is that a fit of challenge and ability exists for the emergence of flow. In the context of digital games, however, enjoyment can even arise independently of flow experience [Lim+11; SHS11], namely when the player's abilities exceed the challenges of the game [NL08; Mek+14]. Ryan and colleagues

[RRP06] further observed that the degree to which the game controls are perceived as intuitive also influences competence. This factor, called intuitive controls, describes the degree to which the player perceives the game controls as meaningful, easy to understand and master, and non-invasive concerning the perception of being within the game world. Intuitive controls as a determinant of the player's enjoyment since they are related to greater perceived competence were not only observed by Ryan and colleagues [RRP06] but also by further works such as [Lim+11; SLW12; TR11]. In summary, it can be stated that the need to experience competence can be satisfied through various mechanisms that digital games fundamentally offer.

The need for relatedness can be satisfied in particular by multiplayer games since they offer interaction possibilities with other players and thus enable a social experience. In particular, the possibility of playing online with other people, thus creating a social setting, means that almost all modern digital games can contribute to the satisfaction of this basic need. In this context, Frostling-Henningsson [FH09] observed that the primary motivation for playing online games is social reasons by offering players cooperation and competition. Beyond the direct satisfaction of the three basic needs by digital games, Ryan and colleagues [RRP06] also observed that the perceived competence and autonomy are related to the experience of presence. They understand presence as "the sense that one is within the game world, as opposed to experiencing oneself as a person outside the game, manipulating controls or characters" [RRP06, p. 350]. According to the authors, a compelling storyline, appealing graphic design, and intuitive controls are particularly important in digital games to create the impression that one is actually in the virtual world. The authors observed that a strong experience of presence is associated with higher perceived autonomy and competence and therefore conclude that presence is directly related to how the digital game satisfies the basic needs of the players. The extensive studies of Ryan and colleagues [RRP06] provide a good basis for explaining the motivational potential and impact of digital games. In this context, the question of why digital games have such a highly engaging and motivating potential is an object of investigation that is not only found in SDT but has been analyzed in the context of a variety of different theories such as the uses and gratification theory [LS04; Col07; Boy+12] and under consideration of differences between players, such as age [Egl+05; GDC04; Boy+12], or gender [LS04; CT07; JAV10; Boy+12]. Although these distinct theories and considerations emphasize different aspects and details in the emergence of motivation for playing digital games, they share the basic assumption that enjoyment is the central motive why digital games are played [Mek+14; Boy+12; SW05].

The enjoyment in digital games is assessed in most publications with questionnaires and only rarely by other methods such as physiological measures [Mek+14]. The most commonly used standardized questionnaire is the IMI [Mek+14]. In this context, the concept of player experience (PX) is often mentioned. PX "describes the qualities of the player-game interaction and is typically investigated during and after the interaction with games" [Wie+16, p. 246]. However, PX is often inconsistently defined [Mek+14] and includes, depending on the publication and the object of investigation, different constructs such as enjoyment, flow, immersion, challenge, tension, presence, emotion, meaning, and curiosity [Mek+14; Wie+16; Abe+20]. The exact consideration of PX is such a broad and multifaceted topic that the detailed presentation would go beyond this chapter's and dissertation's scope. Moreover, it is not of further relevance for this dissertation how the general PX can be constructed. The discussion about a systematic construction and recording is part of current research [Abe+20]. Nevertheless, the terminology of the PX is relevant in the context of this dissertation. Thus, in the context of the publications presented in Chapters 3 – 7, PX is defined as the sum of all constructs that relate to the player's subjective perception while playing the digital game. Thus, depending on the research question and publications, PX may differ between papers and include enjoyment, presence, social presence, arousal, perceived exertion, and embodiment.

2.3.1 Interim Summary

In summarizing Sections 2.1 to 2.3, it can be stated that motivation can be understood as a determinant of why a particular behavior is pursued. According to the popular SDT, motivation can be divided into extrinsic and intrinsic reasons. The more an extrinsic motivator can be aligned with one's sense of self, the more it is internalized, and the more it corresponds to intrinsic motivation. To internalize and maintain intrinsic motivation, the degree to which the basic needs for autonomy, relatedness, and competence can be satisfied by performing the action is vital. Especially in the context of physical activity, the satisfaction of the basic needs and the resulting intrinsic motivation are relevant. The greater the intrinsic motivation and associated sense of enjoyment for performing a physical activity, the more persistently it is performed. Thus, the long-term activity pursuit can only be determined by intrinsic motivation. Hence, considering the physical inactivity in large segments of the population, it can be stated that the basic needs are not being satisfied to a sufficient degree for many individuals when performing physical activities. In contrast, digital games can satisfy people's basic needs for competence, autonomy, and relatedness in a special way and thus have a high inherent motivational potential. However, in most cases, digital games represent a sedentary behavior, the practice of which over a more extended period is accompanied by several different disadvantages. Integrating physical activity into digital games could thus provide a promising approach to solving several problems simultaneously.

2.4 Exergames

Digital games that incorporate physical activity are a well-known concept in the entertainment industry and research. Numerous terms such as *exertainment, interactive video game, activity promoting video game, physical game,* or *active video game* [OY10] exist to describe these kinds of games. However, the most popular term in the research context is *exergame* [OY10]. However, the definition of the term is not uniform and differs between papers concerning various details. For example, depending on the publication, exergame is used as an abbreviation for *Exercise Game* [OY10] or *Exertion Game* [Mue+11]. To unify the definitions and offer a generic definition, Oh and Yang [OY10, p. 9] propose the following definition for exergames:

"An exergame is a video game that promotes (either via using or requiring) players' physical movements (exertion) that is generally more than sedentary and includes strength, balance, and flexibility activities."

Another popular definition is given by Mueller and colleagues [Mue+11, p. 2651]:

"We define an Exertion Game (sometimes called exergame [SHM07]) as a digital game where the outcome of the game is predominantly determined by physical effort."

Both definitions have in common that exertion plays a central role in exergames. Physical effort is understood as the main element of exergames in the definition of Mueller and colleagues [Mue+11]. Oh and Yang [OY10] understand exergames as games that promote exertion but do not see a mandatory relationship between exertion and the outcome of the game. Regardless of the marginal differences, however, it can be stated that exergames require exertion beyond sedentary behavior to control and thus play the game. The form of exertion can consist of different physical activities.

2.4.1 Popular Exergaming Systems

The first commercial exergaming system was introduced in 1982 with the Joyboard from Atari. The Joyboard is a balance board, which is based on the basic control technology of a joystick and can be moved in four different directions. Standing on the board, controls are entered by shifting the body in the corresponding directions. However, only one game – a 2D ski slalom game – has been developed for this system. Although a few exergaming systems followed in the next 16 years (for an overview, see [FM14]), exergaming remained a marginal phenomenon in the field of digital games. This changed with the game Dance Dance Revolution (DDR) from Konami in 1998 [KB98]. DDR is a dance game played with an arcade machine, as

Konami Dance Dance Revolution | Nintendo Wii | Sony EyeToy | Microsoft Kinect

FIGURE 2.2: This figure shows four popular exergaming systems. The references to the images of the respective systems are given in the List of Figures.

shown in Figure 2.2. The core element of this machine is a dance mat on which four different arrows are displayed. The players stand on the dance mat and look at a display in front of them. The display shows arrows on the screen, which are generated to the music's beat. The players' task is to step on the arrows at the right moment. Depending on the song and difficulty level, the movements must be performed so quickly that a pole is attached to hold on to as support for the movements. Depending on the version, the game can be played alone or in pairs. DDR became a very popular exergame, especially in the USA and Japan, and is still being developed further for the Japanese market.

Besides DDR as a standalone arcade machine, exergaming became popular, especially through add-on systems for the major consoles. In 2003, Sony's EyeToy was introduced for the PlayStation 2. As shown in Figure 2.2, EyeToy is a camera with a microphone that can be connected to a PlayStation 2 via USB. With the help of the camera and computer vision, the players' body movements are tracked and can thus be transferred into digital games. A total of 25 games have been released for EyeToy, requiring body movements to control the game and, in most cases, are played standing. By 2008, 10.5 million EyeToy systems had been sold[1].

Another exergaming system was introduced by Microsoft for the Xbox 360 and Xbox One with the Kinect in 2010. Like the EyeToy system, the Kinect, which is shown in Figure 2.2, is based on a camera for detecting body movements. However, unlike the EyeToy camera, the Kinect camera uses depth sensors that enable full-body 3D motion capturing for up to six skeletons simultaneously. The Kinect system has been updated several times with improvements in resolution and tracking capabilities. In total, up to 35 million units were sold by the time production ceased

[1] `https://www.gamasutra.com/php-bin/news_index.php?story=20975` last accessed on Oct. 27, 2021

in 2017[2]. Numerous exergames have been developed for the Kinect systems, which in most cases involve full-body movements to control the game[3]. Furthermore, the Kinect can also be used for Windows applications with the appropriate drivers. Due to the good development interface that Microsoft has made available for the Kinect, the low acquisition costs, and the stable full-body tracking, the Kinect can often be found as an exergaming system in scientific work and exergames specially developed for this purpose. Thus, the work which will be presented in Chapter 3 also used the Kinect for body tracking.

Probably the best-known exergaming system, however, is Nintendo's Wii, which was released in 2006. Unlike systems such as EyeToy or Kinect, the Wii's body-motion control is a fundamental part of the console and not just a unique piece of additional hardware. As shown in Figure 2.2, a wireless controller is required to interact with the Wii. Using infrared sensors and accelerometers, the Wii can calculate the position of the controller relative to the screen and the rotations and movements of the controller. Due to the inherent motion aspect of the console, body movement has become a central aspect of the most popular games for the Wii. The most well-known game in this regard is Wii Sports [EAD06]. In this game, five different sports are integrated, which all require body movements, mostly while standing, to control the game. Wii Sports has sold about 116 million copies by 2020, making it one of the most successful video games of all time[4]. Another popular exergame for the Wii was released with the game Wii Fit [EAD07]. To control the game, a balance board is used, which utilizes various sensors to detect the weight and inclination of the player. Wii Fit contains 48 fitness exercises, which include aspects such as balance, aerobics, or muscle building, and has been sold about 44 million times by 2020[5]. Due to the intuitive controls of the Wii and the variety of different sport exercises in the games Wii Sport and Wii Fit, the Wii was and sometimes still is a frequently used exergaming system in research regarding the effects of exergames.

Even though exergames were a great success in terms of sales, the most prominent games and systems were introduced in the 2000s. Except for DDR, which was constantly developed further, the development of exergames was not focused on further by the major manufacturers. This absence continued until 2019 when Nintendo released Ring Fit Adventure [Dev19], a new exergame system for the Nintendo Switch. This system builds on a pilates ring specially developed for this game, which in combination with a leg strap, can recognize and demand numerous body movements of the player. The game has already sold over 11 million copies as of

[2] https://www.fastcompany.com/90147868/exclusive-microsoft-has-stopped-manufacturing-the-kinect last accessed on Oct. 27, 2021

[3] For an overview see https://www.reddit.com/r/xboxone/comments/fr14xh/all_xbox_one_kinect_games_list/ last accessed on Oct. 27, 2021

[4] https://www.vgchartz.com/game/226191/wii-sports/?region=All last accessed on Oct. 27, 2021

[5] https://www.vgchartz.com/game/226182/wii-fit/?region=All last accessed on Oct. 27, 2021

August 2021, making it one of the most successful titles on the Nintendo Switch [NC21].

2.4.2 Effects of Exergames

The fundamental idea of exergames is to combine the inherent motivational potential of digital games with physical activity. The impact that exergames can have on players, especially in comparison to conventional physical activity, is the subject of a multitude of existing research studies.

Gao and Madryk compared three different exergaming conditions in their paper [GM12]. They first created the game GrabApple, which is controlled using the Kinect and full-body movements and prompts movements such as jumping, ducking, and running around through various mechanisms within the game. In a second condition, they created a game version that replaces all body movements with interactions using a computer mouse. Further, the authors created a version that required the participants to run on a treadmill with no additional game-like elements as a third condition. The treadmill's speed was permanently adjusted during the game so that the subjects always exercised at about 64 – 76% of their maximum heart rate. All versions were played for 10 minutes. The authors observed that running on the treadmill and playing the exergame resulted in significantly higher exertion than playing with the mouse, but that the exergame and treadmill conditions did not differ. Regarding enjoyment (called fun in the paper), the authors observed that the exergame and mouse condition led to significantly higher scores than the treadmill condition. The exergame version also led to higher enjoyment scores than the mouse version of the game, which was confirmed in another paper by Gao and Madryk [GM11] on the same game. Similar results were found by McDonough and colleagues [McD+18] who examined three different exergaming conditions in terms of activity level and perceived enjoyment with college students. The first two conditions consisted of two different games for the Kinect (Just Dance [Ubi+12] and Kinect Adventure's Reflex Ridge [Stu10]). The third condition consisted of a running session on a treadmill at 4.0 mph. In all conditions, the respective activity was performed for 20 minutes. The authors observed that both exergaming conditions led to more enjoyment than running on the treadmill, but the activity levels of the treadmill were higher than those of both exergames. Further, Garn and colleagues [Gar+12] investigated in their study what influence the game WiiFit has on college students not adhering to the WHO physical activity guidelines. In this study, each subject played five different mini-games within the WiiFit game for 10 minutes each. The authors observed that intention to exercise in the future improved significantly after the Wii intervention compared to before the intervention. The comparison of the enjoyment regarding conventional sports exercises and the Wii intervention showed a significant improvement in obese students.

In addition to the investigation of the effects of one-time exergame interventions, the work of Rhodes and colleagues [RWB09] and Warburton and colleagues [War+07] investigated the potential of exergames over a longer period of time. In the study by Rhodes and colleagues [RWB09], 32 male college students, all of whom regularly engaged in physical activity, were randomly assigned to two conditions. In both conditions, participants were asked to exercise on a stationary exercise bike – a so-called exercycle – in a laboratory setting. In the exergame condition, the exercycle was modified to control various PlayStation 2 games using the exercycle. In the control condition, subjects were asked to train only on the exercycle. During the studies' period of six weeks, all subjects could freely choose the amount of training on the exercycle. However, prior to this, all subjects were given a recommended exercise intensity of 30 minutes, three days a week, at a moderate intensity. The authors observed that subjects in the exergame condition showed up for exercise significantly more often than subjects in the control condition. They also found that the subjects' enjoyment was significantly higher in the exergame condition than in the control condition. In addition, they found through regression analysis that the players' enjoyment significantly influenced the higher training frequency in the exergaming condition. The same study design was used in a study by Warburton and colleagues [War+07] with 14 male college students, who, in contrast to the study by Rhodes and colleagues, all did not regularly engage in physical activities. In addition, the focus of Warburton and colleagues' work was not on player enjoyment but on the physical benefits that the exergame condition provides. The authors observed that as in Rhodes and colleagues [RWB09], subjects in the exergame condition exercised significantly more often with the exercycle. In addition, subjects in the exergame condition significantly improved endurance performance, leg power, and vertical jump after the 6-week intervention. In the control condition, there was no significant improvement in these constructs after the intervention. Although Warburton and colleagues did not measure subjects' enjoyment, the higher training frequency in the exergame condition suggests that the exergame has a property that motivates voluntary use. In the context of Rhodes and colleagues' results [RWB09], it seems reasonable to assume that the perceived enjoyment of the subjects while playing the exergame is the underlying reason.

Based on these studies, it can be concluded that exergames can offer an advantage in enjoyment compared to conventional sports exercises and physical activity. Accordingly, the meta-review by Lee and colleagues [Lee+17] based on 45 papers, including all age groups, concludes that exergames have an inherent motivational property that leads players to enjoy performing the required physical activity and thus encourages players to continue performing it. Consistent with this, the meta-analysis by Gao and colleagues [Gao+15] based on 35 papers concludes that exergame interventions in children and adolescents provide significant added value in terms of enjoyment compared to laboratory-based exercise and field-based physical activity and can even generate higher heart rates and provide various physiological benefits such as better cardiovascular fitness. However, most of the results of the studies refer to the effects of exergames for one-time interventions. Currently, there is still scarce knowledge on the long-term effects, so that no reliable statement can be made about the long-term use of exergames [SLL17]. However, the studies that exist show varying results regarding participation and exercise frequency depending on the application context and the game used [Kar17]. Nonetheless, exergames can have a high motivational appeal to individuals even over a more extended period [War+07; RWB09] and thus encourage voluntary exercise.

2.4.3 Exertion in Exergames

Regarding the motivational advantage that exergames can offer over conventional physical activities, a consensus has emerged in the published works on the topic. Beyond enjoyment, however, exergames are also studied in terms of their physiological effects. In this context, the physiological effects surveyed can differ greatly between papers. Depending on the research question, effects may include basic motor skills [Ver+15], grip strength [War+07], jumping power [War+07], flexibility [War+07], blood pressure [War+07], functional strength [SEJF17], balance [SEJF17], and agility [SEJF17]. However, the most commonly measured physiological effect is the player's exertion level or activity level. Through the measured exertion that the exergame requires from the player while playing, it is possible to determine to what extent the exergame contributes to the WHO's physical activity guidelines as described in the introduction. Exertion is usually measured in most papers on exergames using either maximal oxygen uptake or heart rate. To measure maximal oxygen uptake, an appropriate face mask is used, which has to be worn while performing the physical activity. The maximum oxygen uptake can be calculated by measuring various parameters such as the oxygen concentration and volume of inhaled and exhaled air. Since the necessary setup to determine the maximum oxygen uptake is complex and not suitable for every exergame due to the use of the face mask, the measurement of the exertion via heart rate is widely used. The heart rate describes the number of heartbeats in a certain period, usually per minute. Sensors placed on the skin are particularly suitable for measuring the heart rate during physical activity. The simplest and most popular variant is a wireless chest strap worn under the chest, measuring the heart rate through two skin electrodes. Depending on the question, different aspects of the heart rate can be interesting. However, raw heart rate is problematic to interpret because it depends on many factors, such as a person's age and athleticism. Hence, the average heart rate during the performance of a physical activity cannot be compared between two individuals if a statement about exertion is desired. To establish comparability, the measured heart rate

TABLE 2.1: Classification of physical activity intensities based on %HRR and %HR following the ACSM's guidelines for exercise testing and prescription [SM+13].

Intensity	$\%HRR$	$\%HR$
Very light	< 20	< 50
Light	$20 - 39$	$50 - 63$
Moderate	$40 - 59$	$64 - 76$
Hard (vigorous)	$60 - 84$	$77 - 93$
Very hard	≥ 85	≥ 94
Maximal	100	100

must be normalized. For this purpose, the proportion of the measured heart rate to the maximum heart rate (%HR) or the proportion to the heart rate reserve (%HRR) is usually used. For both measures, the theoretical maximum heart rate (HR_{max}) in beats per minute must be measured first. Depending on the underlying work, HR_{max} can be calculated either by $211 - (0.64 * age)$ [Nes+13] or $208 - (0.7 * age)$ [TMS01]. However, the most commonly used formula is $220 - age$ [SM+13]. For the calculation of %HR, the measured heart rate is then expressed as a percentage of the maximum heart rate. In addition, for the calculation of %HRR, a resting heart rate (HR_{rest}) must be recorded. The %HRR can then be calculated using the following formula: $\%HRR = \frac{HR - HR_{rest}}{HR_{max} - HR_{rest}}$

The relationship between %HR, %HRR, and physical activity intensity is shown in Table 2.1. However, the maximum heart rate is a problem for both constructs because it is only calculated theoretically, and in reality, it can deviate significantly from the real value, e.g., due to athleticism [Why+08]. Therefore, for comparison of exertion through heart rate between different individuals, especially for populations in a homogeneous age group, normalization of the current heart rate using only a baseline measurement can be sufficient.

In addition to measuring exertion based on physiological correlation, perceived exertion is also frequently recorded. Perceived exertion is a subjective assessment of a person for a performed physical activity. The Borg scale [Bor98] has become a popular tool for recording perceived exertion. The Borg scale ranges from 6 to 20 (6 = not at all strenuous, 13 = somewhat strenuous, 20 = maximum strenuous). The given value of the Borg scale can be multiplied by 10 to approximate the corresponding heart rate. In the context of work on exergames, perceived exertion is often recorded because increased perceived exertion can be associated with a reduction in enjoyment [ARK94; HR89; EHP08; EPP11]. In addition, some authors of papers on exergames have observed that exergame interventions did not result in a corresponding increase in perceived exertion when there was a significant increase in physiological exertion [War+09; HSW09]. Thus, the exergames were able to distract from exertion. However, the influence of exergames on exertion, especially in contrast to conventional physical exercise, is not evident. On the one hand, different works conclude that exergames can achieve similar or even higher exertion compared to conventional exercises [Gao+15; GM12; RWB09; War+07]. On the other hand, some authors observed lower exertion when playing exergames compared to performing conventional exercises [Kar17; GZS13; McD+18; Per+19; Gra+07]. Although a variety of reasons exist for this, the exergame used in particular is a significant reason for the difference in exertion between the works. For example, there are substantial differences in intensity [BM11; Miy+10] between the games in Wii Fit and Wii Sports and DDR alone. In addition, the study by Miyachi and colleagues [Miy+10] showed that none of the games of Wii Fit or Wii Sports could produce vigorous intensity.

Nevertheless, even if exergames are thus not always suitable as a substitute for physical activities, they have high motivational potential, are usually played while standing, and generate an exertion that significantly exceeds that of a conventional sedentary digital game [DP15; Gra+07]. Thus, they are particularly suitable as a supplement or additional measure to reduce sedentary behavior and encourage and stimulate physical activity. Because of these characteristics, exergames have been used beyond the application context of general physical activity in various contexts, such as the following:

- Prevention and treatment of childhood obesity [ACC19; ZG16; Val+21; Mac+17]
- Prevention of falls of older adults [Fan+20; LDK14; Pac+20]
- Treatment of depression [Dra+20; LTF16]
- Improving cognitive performance [GM12; AH+12]
- Neurological rehabilitation [MR+17; Mur+17]

Besides the different positive effects of exergames in the areas mentioned above on the relevant constructs, especially in comparison to conventional approaches, the increased enjoyment of the subjects and patients is named a significant effect by these studies across all application areas. Due to the central importance of the perceived enjoyment of players of exergames, several different works have addressed the question of how to increase the enjoyment of exergames further.

Peng and colleagues [Pen+12] developed the exergame Olympus to investigate the influence of game elements on player enjoyment. Using a Wii controller and a dance mat, the player controls a virtual character through a scene in ancient Greece. The game has been developed in such a way that autonomy and competence supporting elements can be optionally activated. Character customization, self-selectable character enhancements, and interactive dialogs with non-player characters were developed as autonomy supporting elements. A dynamic difficulty mechanism, display of points informing player performance, and achievements were developed for competence support. In the control conditions, the supporting mechanisms were turned off, and players had no opportunity to make their own decisions in the game. In a study with 160 subjects after 15 minutes of gameplay, the authors observed that subjects in the conditions with the supporting mechanisms had significantly higher enjoyment and motivation for future play than in the respective control conditions without the supporting mechanisms. Consistent with this, the review by Lyons [Lyo15] also concludes that especially feedback, challenge, and rewards are mechanisms to increase the enjoyment of players in exergames.

Ketcheson and colleagues [KYG15] have developed three different exergames in their work that can be controlled using an exercycle and a gamepad. In all exergames, they integrated a mechanic called HR Power-ups. The idea is that players in the respective exergames receive a power-up if they voluntarily exercise at a specific heart rate (65%HRR in the paper) for a certain amount of time using the exercycle. In a study with 20 subjects, the authors observed that the HR power-up mechanism led to significantly higher exertion in two games. The mechanism was evaluated as enjoying, but an inferential statistical comparison is missing in the paper.

Stach and Graham [SG11] investigated the extent to which haptic feedback can make an exergame seem more real and thus increase player enjoyment. For this purpose, they developed the exergame Pedal Race. In the game, the player controls a virtual tricycle on a race track. On the race track, there are different areas, which have either asphalt, ice, or mud as underground. Depending on the surface, the resistance of the exercycle is changed. In a study with 24 subjects, the authors observed that the change in resistance depending on the surface led to a higher degree of realism and more enjoyment than a control group with no change in resistance.

Murray and colleagues [Mur+16] developed an exergame that can be controlled by a rowing machine. The exergame consisted of a rowing simulation, which was developed in three different versions. In the control version, the test persons rowed alone without the exergame. In the second version, the subjects rowed alone but controlled a virtual boat in the exergame. In the third condition, subjects were told a second rower would play the game parallel but in another room with the player. However, only the time of the slower rower would count for both of them afterward. In addition, the rowing ability of all subjects was determined in advance in all conditions. In the group with the teammate, the player was also told that the teammate's pre-measured performance was 40% better. However, the teammate did not exist and was controlled by corresponding software. The subsequent task was to row as far as possible for 9 minutes. In the condition with the teammate, the teammate's boat was, on average, displayed as slightly faster than the player's boat. In a study with 60 participants, the authors observed that both versions of the exergame resulted in greater distance rowed and more enjoyment than the control condition. In addition, the social setting in the co-player condition significantly increased distance but not enjoyment compared to the exergame single-player condition. A similar conclusion was reached in the work of Irwin and colleagues [IFK13], who observed in an exergame for EyeToy with 115 subjects that subjects who played together with an online partner could hold a plank significantly longer.

Song and colleagues [Son+10] also investigated the influence of competition and competitiveness on players' enjoyment and exertion. They had 72 subjects play the Wii Fit game Hula Hoop. Beforehand, the subjects were divided into a high or low competitiveness group by a median split. Then, the players played the game, which involved performing as many virtual hula hoop spins as possible on the Wii Balance Board, either without or with a competitive mechanism. This mechanism showed a pre-recorded video of one person's performance steadily improving. Subjects were tasked with playing the game for a minimum of 10 minutes and a maximum of 18 minutes. The authors observed that the subjects in the condition with the competitive mechanism showed significantly more exertion than the subjects without the competitive mechanism. Regarding enjoyment, the authors could find out that subjects with high competitiveness enjoyed the version with the competitive mechanism more than the subjects with low competitiveness. Likewise, subjects with low competitiveness enjoyed the version without the competitive mechanism more than subjects with high competitiveness. Furthermore, Marker and Staiano elaborated [MS15] in their review that exergaming with other individuals has several positive effects in terms of enjoyment, exertion, and even weight loss compared to solitary exergaming play. The authors also examined the differences between competitive and cooperative exergaming and found that cooperative exergaming offers significant benefits over competitive exergaming in terms of enjoyment.

In summary, it can be stated that different mechanisms within exergames can strengthen the enjoyment and the respective physical effects. These mechanisms can be divided with regard to competence [Pen+12; Lyo15; Mat+17], autonomy [Pen+12; Lyo15; Mat+17] and relatedness [Mur+16; IFK13; Son+10; MS15; Mat+17] which are influencing factors for enjoyment in digital games. An exception is the approach of Stach and Graham [SG11] presented above, who increased the player's enjoyment by integrating haptic feedback into their exergame. Thus, the authors have increased the degree to which the game seems real. With regard to the factors influencing enjoyment in digital games presented by Ryan and colleagues [RRP06] in Section 2.3, it can be seen that Strach and Graham's approach did not aim at increasing the autonomy, competence, or relatedness but instead aimed at increasing the players' experience of presence. The experience of presence was identified as an influencing factor for the enjoyment in digital games [RRP06] and exergames [Son+10]. This leads to the question of how the presence experience of exergame players can be increased in order to enhance the player's enjoyment and thus intrinsic motivation.

2.5 Virtual Reality

One way to create a high experience of presence is by using modern VR technology. A perfect VR would be a completely real appearing but not existing reality that would allow the masking of reality and immersion in any computer-generated scenario. This would require a system to manipulate all sensory inputs that exist to perceive the reality [Dör+13]. While manipulating all sensory impressions is a distant dream, simulating realistic visual impressions is the core element of current VR systems.

The basis of every VR system is the combination of hardware for the calculation and display of virtual cues and corresponding software that provides the content. The displayed content within a VR system, which the user can perceive, is called virtual environment [Dör+13]. Within this virtual environment exists a virtual camera, which represents the eyes of the user. Everything in the camera's field of view should be displayed as if it were in the field of view of the eyes; everything outside the field of view should not. In order to display a realistic virtual environment, two things are necessary in particular. First, a stereoscopic representation of the visual content is required. The virtual camera must record the virtual environment from two slightly offset points. The distance between these points must correspond to the actual distance between the user's eyes. The recorded content is then played back separately for each eye so that both images are combined in the user's brain to form a single image and thus to create a three-dimensional spatial impression. The second requirement for the realistic rendering of a virtual environment is the change of the virtual camera depending on the player's head movements. If persons in the real move their heads, the visual impression changes because of the position or rotation of the eyes. This change must be transferred to the virtual environment accordingly.

Although various technologies exist that can implement these requirements, two different technologies have become established in particular. One approach is the Cave Automatic Virtual Environment (CAVE) system. The core element of the CAVE is a room-sized cube. Projectors are installed outside this room, which can project the virtual environment stereoscopically on up to all six walls of the room. The user is inside the room and wears 3D glasses that separate the stereoscopic image for the eyes. The user's position is captured using motion capturing technology and changed accordingly in case of movements so that the user has the impression of walking through the virtual world. For this purpose, the CAVE is usually connected to a computer cluster that performs the calculations and adjusts the image of the projectors. However, setting up and operating a CAVE is complex and expensive;

hence another technical approach has become popular. This technology is known as head-mounted displays (HMDs).

An HMD is a goggle-like device that is worn on the head. The HMD usually shields the user's view entirely from the real world. By using one display and a corresponding lens per eye, different images can be displayed for each eye to create a stereoscopic image. In addition, HMDs have sensors that can detect the rotation of the head and adjust the virtual image accordingly. The simplest version of such an HMD is the Google Cardboard which is a cardboard holder into which two lenses and a smartphone can be inserted. The smartphone's acceleration sensors can detect a rotation of the head and transfer it to the virtual environment. However, such a setup does not allow movements through space, as these cannot be tracked. Thus, cardboard HMDs only offer three degrees of freedom. More complex HMD systems that offer increased degrees of freedom are the Oculus Rift, Oculus Quest, HTC Vive, and Sony PlayStation VR. In addition to the rotation of the head, these systems can also detect a change in the position of the head and transfer it to the virtual environment accordingly. The Oculus Quest and the HTC Vive even enable the detection of the position change of the HMD in a larger room. The player can thus walk through a room, thereby changing the virtual camera's position in the virtual environment and having the impression of walking through a virtual world. This technology is referred to as room-scale VR. The tracking technology for determining the position change of the HMDs can either be carried out by the HMD and corresponding cameras in the HMD itself, as in the Oculus Quest or is dependent on external markers, as in the HTC Vive. Depending on the technology, the maximum walkable area is either $10m * 10m$[6] or $15m * 15m$[7]. All HMDs rely on a corresponding computer or processor. In the case of the HTC Vive or the Oculus Rift, this is an external PC; in the case of the Oculus Quest, all calculations take place on a system on a chip built into the HMD. The connection of the HMD to an external PC takes place either via cable or, with the introduction of the Vive Wireless Adapter in September 2018, also wirelessly. Although the various HMDs differ in technical details such as field of view, frames per second, resolution, and latency, their basic functionality is similar. In addition to the HMD as the core element of a VR system, most VR systems have special controllers that track and transfer hand movements in reality into the virtual environment, like the HMD. Thus, users of a VR system can intuitively act three-dimensionally in space, just as they would in the real world. Furthermore, some VR systems, like the HTC Vive, offer the use of additional trackers. Like the controllers, these trackers can be rotated and moved in space, but they do not have any buttons for interaction. They can be used for tracking objects or joints on the player's body.

By using a VR system for digital games, a fundamental paradigm shift arises

[6] https://www.vive.com/de/support/vive-pro-eye/category_howto/minimum-and-maximum-play-area-size-for-more-than-2-base-stations.html last accessed on Aug. 18, 2021

[7] https://uploadvr.com/oculus-quest-guardian-size-increasing/ last accessed on Aug. 18, 2021

[DK18]. While in conventional games, the player usually sits in front of a screen and controls the gameplay through a controller or mouse and keyboard; a VR system puts the players into the game in such a way that the illusion is created that the game is taking place around them and not just on a screen in front of them. Furthermore, using room-scale technology and appropriate controllers, body movements to interact with the virtual environment also become a central part of the gameplay. Hence, in terms of Oh and Yang's exergame definition [OY10] mentioned in Section 2.4, room-scale VR systems can be considered to have an inherent exergaming component. Thus, even though the exertion required has to be considered a function of the particular game, the sedentary gameplay of conventional games is replaced by standing and moving around the room. Moreover, this fundamental property of room-scale VR systems allows movement and thus exertion to be considered as a central element in game development. Furthermore, VR systems offer a high degree of presence, which can potentially have a positive impact on the players' enjoyment while playing an (exer)game [RRP06; Son+10]. To better understand this term in the context of the following chapters, a precise definition of presence and the related construct of immersion is given in the following subsection.

2.5.1 Immersion and Presence

In the characterization of VR systems, two terms are frequently mentioned: Immersion and Presence. Even in scientific publications, it is not always possible to clearly distinguish between the two terms; in fact, they are often used synonymously. In essence, immersion refers to the degree to which users can be absorbed by a fictional world. The exact definition of immersion is not clear and can be understood differently depending on the underlying work. Slater and Wilbur [SW97, p. 604 – 605] consider immersion in their work as "a description of a technology, [that] describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant." Inclusive describes the degree to which the real world can be excluded. Extensive describes the degree to which the user's sensory modalities can be considered. Surrounding describes the extent to which the virtual world is displayed panoramically and not just limited to a narrow field. Vivid describes the extent of the system's resolution and display quality [SW97]. Accordingly, immersion can be understood as an objective characteristic of a technical system that describes the degree to which the user is integrated into a virtual environment [Sla09]. This would mean that the better the technical characteristic of a system, the more this technology allows the user to be immersed in a virtual world. However, this definition neglects the content of the virtual environment. Especially in the context of digital games, the immersion into the virtual world is not only dependent on the technical system but, as in the case of books, characterized by a variety of content elements such as character, world, or storyline [EM05]. Therefore, the authors Ermi and Mäyrä have designed the SCI model, which divides immersion in games into three categories: sensory immersion, challenged-based immersion, and imaginative immersion [EM05]. Sensory immersion is synonymous with the immersion concept of Slater and Wilbur [SW97], and describes the degree of technical involvement in a virtual game environment by a system. Challenge-based immersion describes the degree to which the game is "able to achieve a satisfying balance of challenges and abilities." [EM05, p. 7]. Thus, challenge-based immersion is similar to one of the main influences for satisfying the basic need for competence in digital games as presented in Section 2.3, resembling the underlying concept of flow theory [Csi90]. Imaginative immersion describes the degree to which a digital game "offers the player a chance to use her imagination, empathize with the characters, or just enjoy the fantasy of the game." [EM05, p. 8]. With a high imaginative immersion, the player is absorbed by the game world and the story and can identify with a game character. This part of immersion is also often called mental immersion [Muh15; Lis21]. Even though different aspects are important for immersion in a fictional or virtual world, in the context of this dissertation, immersion is understood as an objective describable characteristic of a system and thus in line with Slater and Wilbur's understanding of immersion [SW97]. The work presented in Chapters 3 – 7 considers the advantage of VR systems in contrast to conventional setups with a TV screen due to the higher sensory immersion. The importance of the other immersion dimensions is not questioned, but they are not considered in the work that forms the body of this dissertation. Based on the technical understanding of immersion, it can be said that modern HMD VR systems offer a higher degree of immersion compared to conventional non-VR setups with a screen or projector as an output device.

The immersion of a system has a direct influence on the presence experience of a user [SW97; SU94], which is often understood as the feeling of being there [Hee92]. In contrast to the objectively describable property of immersion, presence describes the subjective state of consciousness of actually being in the presented virtual environment and not in the actual reality [SW97; SVS05]. A prerequisite for accepting the virtual world as the real world is the willing suspension of disbelief [Col17], which characterizes the conscious suppression of the simulated stimuli as inauthentic [Lee04]. This definition of presence is thus the same as the understanding of presence presented in Section 2.3 by Ryan and colleagues [RRP06], who identified presence as an influencing factor for enjoyment in digital games. Presence can further be divided into two forms: spatial presence and social presence. Spatial presence describes the degree to which a user perceives a virtual environment or space as real [LJ15]. Social presence describes "the degree to which a user feels access to the intelligence, intentions, and sensory impressions of another" [Bio97, p. 19]. Except for the paper [BSM19], which is presented in Chapter 5, the publications in Chapters

3 – 7 deal exclusively with spatial presence. Thus, in the following chapters, presence is understood as spatial presence if not stated otherwise. While the immersion of a system can be described objectively, a corresponding tool is necessary for the survey of the subjective presence experience. In the context of the work presented in Chapters 3 – 7, presence was surveyed with the Igroup Presence Questionnaire (IPQ) [SFR01; Sch03]. This questionnaire contains 14 items, individually assessable on a scale of 0 – 6 (0 = low, 6 = high). The questionnaire has three subscales: spatial presence, involvement, and experienced realism. Spatial presence is synonymous with the already defined understanding of spatial presence. Involvement describes the focus of attention on the virtual environment. Experienced realism describes how real the virtual world seemed compared to the real world [Sch03]. Furthermore, the IPQ captures the general presence with an item that describes the general sense of being there [Hee92] and has a strong factor loading with all subscales, especially with the spatial presence subscale.

Thus, it can be concluded that modern HMD VR systems, due to their technical features, can integrate the user more comprehensively into a virtual environment than it is possible with conventional non-VR setups. Since immersion has a direct influence on the experience of presence, highly immersive HMD VR systems can lead to an increase in the experience of presence compared to less immersive non-VR systems with the same content [PPM19; Kim+14; BC17]. A particular aspect of this is the simulation of a virtual body. Using VR technology, a user can be shown a virtual body that behaves similarly or exactly like the real one. Through the immersive representation of the body with the help of modern VR technology, the feeling can be suggested that the virtual body is one's own [KGS12; IKH06; MS13; PE08]. This phenomenon is referred to as the sense of embodiment, which according to Kilteni and colleagues, is defined as "the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body" [KGS12, p. 374 – 375]. Embodiment can be divided into three dimensions: self-location, agency, and body ownership [KGS12]. Self-location describes the spatial sensation of being inside a body. Body ownership describes the perception of the body as one's own body and thus as the source of bodily sensations. Agency describes the perception of being able to control the body fully [KGS12]. An increased sense of embodiment can have a positive influence on the experience of presence [KGS12; KPB14] and thus on the enjoyment of players in digital games [KPB14].

As shown in Section 2.3, presence is an influencing factor for the enjoyment in digital games [RRP06] and for exergames [Son+10]. Compared to conventional non-VR systems, modern, highly immersive VR systems can increase the experience of presence and thus also the enjoyment. Concerning how the enjoyment in exergames can be further increased to counteract the lack of enjoyment and thus intrinsic motivation for engaging in physical activities, the use of modern VR systems would be a promising approach. The consideration of these so-called VR exergames will be presented in the next section.

2.6 Virtual Reality Exergames

Exergames that are played with the help of a modern CAVE or HMD system are referred to as VR exergames in the following. The research field on VR exergames is still in its infancy due to the rising availability of the required technology. The potential benefits of VR exergames have been considered in comparison to conventional physical activities without game-like elements, on the one hand, and compared to non-VR exergames, on the other.

Zeng and colleagues [ZPG17] used an exercycle connected to a PlayStation VR system in their work. The game could be operated by pedaling and leaning left and right. This allowed players to play either a car racing game or a bike simulation in VR. In a second condition, the exercycle was also used but without the use of VR or games. The authors had 12 college students play both versions of the game for 20 minutes each in a study. The authors observed that the VR exergame condition led to significantly more enjoyment and significantly less perceived exertion than the control condition despite similar physical exertion. Arndt and colleagues [APVA18] developed a VR exergame for their study, which required a stationary rowing machine as an input device. In their game, the player rowed across a virtual lake in a virtual rowing boat. The VR system used was the HTC Vive. To test the effects of their VR exergame, the authors created a control condition in which the users had to row on the same rowing machine without the use of VR or game-like elements. In a study, 16 subjects who were primarily skilled rowers tested both conditions in randomized order. They had to row 500 meters in each condition. Regarding different rowing metrics such as consistency, recovery, and rhythm, the authors observed that the subjects in the VR condition performed slightly better and showed greater enjoyment than the subjects in the control condition. Using the same exergame, Schmidt and colleagues [Sch+18] also observed that an HMD version of the exergame with the HTC Vive resulted in a significantly higher presence experience than a CAVE variant of the exergame.

One of the first studies to compare VR exergames with non-VR exergames is the work of Yoo and Kay [YK16]. In this work, the authors developed three different versions of an exergame in which the players run on the spot, allowing them to run through a virtual world while avoiding obstacles. The game's goal is to run as fast as possible through the virtual world without colliding with any obstacle. In the first condition, a laptop display was chosen as the output device. In the second condition, a projector was used. In the third condition, a Cardboard HMD was used. The player's movements were captured with the same sensor in all conditions. In one study, 18 subjects played all versions of the game in randomized order. While the authors did not perform an inferential statistical analysis of their data, the qualitative data suggest that the projector and HMD were rated positively in terms of their level of immersion. In addition, the usability of the VR condition was rated higher than in the other two conditions.

Shaw and colleagues [Sha+15b] have developed an exergame for the Oculus Rift, which can be played on an exercycle. The player controls a virtual character on a semi-linear course and has to avoid obstacles. The speed of the game depends on the pedal speed of the exercycle. In addition, the player can avoid obstacles by leaning left or right and ducking. These movements are captured with a Microsoft Kinect. The course is procedurally generated and is thus not limited in length. In order to systematically study the effects of this VR exergame, the authors also implemented two other versions. In the second condition, the game is played as a non-VR exergame in front of a conventional PC monitor. In the control condition, subjects train conventionally on the exercycle without VR and game-like elements. In a study, 26 subjects played all developed versions in random order for ten minutes each. The authors observed that both exergame versions resulted in a significantly farther traveled distance than the control condition. However, the two exergame versions did not differ. In terms of enjoyment, the authors observed that both exergame versions could generate significantly more enjoyment than the control version and that the VR exergame version could generate significantly more enjoyment than the non-VR exergame version.

McDonough and colleagues [McD+20] used the same approach as Zeng and colleagues [ZPG17] and connected an exercycle to a PlayStation VR system. This system could be used to play either a car racing game or a bicycle simulation. In a second condition, the authors connected the exercycle to an Xbox 360. By using the exercycle, a dirt-bike racing game could be played. In a third condition, which served as a control condition, subjects trained conventionally on an exercycle without a VR system and game-like elements. In a study, 49 subjects played all three developed versions in random order for 20 minutes each. The authors observed that the VR and control conditions significantly increased exertion compared to the non-VR exergame version. Furthermore, enjoyment was significantly higher in the VR condition than in either of the other conditions. In addition, the perceived exertion in the VR condition was significantly lower than in the control condition, although the physical exertion did not differ between these two groups.

In conclusion, VR exergames can have advantages over conventional exercise but also over non-VR exergames in terms of enjoyment, physical exertion, and perceived exertion. However, it is noticeable that all of the studies presented here chose a repetitive motion such as cycling, rowing, or running on the spot. The movement controlling the game is thus always identical and can be performed automatically without conscious attentional focus on the movement. The gameplay does not change the movements necessary to interact with the game, as in the non-VR exergames presented in Section 2.4.1. While there are games such as the one by Shaw and colleagues [Sha+15b], where additional movements like leaning to the side are necessary as interaction, the strenuous primary interaction is always a non-changing monotonous physical movement. Popular VR exergames, such as BeatSaber [Gam19], which is one of the most successful VR games of all time[8], use a different approach. In BeatSaber, the players must smash blocks coming toward them in rhythm with a lunging punching motion in the right direction. In addition, the players must avoid obstacles coming at them by ducking or moving sideways. The gameplay thus always requires new and mostly unpredictable movements that demand a conscious focus and cannot be automated. A first VR exergame that has a similar approach to combining movement and gameplay is the game Astrojumper, which was developed by Finkelstein and colleagues [Fin+11] for a three-sided CAVE. The player flies through a space environment in the game and must avoid incoming planets by ducking, jumping, or moving sideways. Various sensors worn by the player on central body parts allow collisions with the body and planets to be detected. In a study with 30 subjects, the authors observed that after 15 minutes of play, Astrojumper was able to generate the desired exertion of $50 - 85\%$ of the maximum heart rate in most participants. In addition, however, the authors surprisingly observed a positive correlation between perceived exertion and perceived enjoyment/motivation in the game. However, the authors did not include a comparison group.

Nonetheless, the finding that high perceived exertion levels are associated with high enjoyment levels contrasts with the findings of Zeng and colleagues [ZPG17] and McDonough and colleagues [McD+20], where higher motivation was associated with lower perceived exertion scores. A significant difference between the two papers is the purpose of VR in each. In Finkelstein and colleagues' work, VR serves as a fun-enhancing element, but it is not intended to distract from the movements. In Zeng and colleagues [ZPG17] and McDonough and colleagues [McD+20], VR is used somewhat as a distractor from a strenuous activity by shifting the focus away from the physical activity and toward a virtual environment. Due to the highly immersive technology and the resulting strong experience of presence, the real world in which the exertion is performed is blocked out, and the virtual world is accepted as the real world without the presence of physical exertion. In a paper by Mestre and colleagues [MEM11], this distraction effect was investigated in the context of exergames. The authors observed that playing on an exercycle while simultaneously viewing a virtual world via projectors around the user resulted in significantly more enjoyment and less perceived exertion than riding without additional projection. In addition,

[8] `https://www.spglobal.com/marketintelligence/en/news-insights/blog/top-10-vr-games-by-revenue` last accessed on Nov. 19, 2021

the authors found that the projection of the virtual environment created a dissociative attentional focus while riding, directing users' attention away from physical exertion and towards environmental stimuli. Although this study did not use VR technology, it demonstrates the possibility of using immersion to distract from exertion. Here, as in the work of Zeng and colleagues [ZPG17] and McDonough and colleagues [McD+20], VR technology can achieve even more significant effects than non-VR systems, as they can create a higher experience of presence than non-VR systems, and thus can distract focus from the real world to an even greater extent. Also, besides the research on exergaming, the distractive effect of VR from unpleasant situations has been applied to different contexts [Lis21; Hof+11].

While the distraction from strenuous repetitive movements through VR technology is a promising approach, it does not take advantage of the possibilities that room-scale VR systems offer. By incorporating a player's body and a large play area, far more and constantly new interactions can be demanded of the game. Further, the approach of distracting from a strenuous activity using VR technology accepts the fact that some persons have no enjoyment in performing a strenuous activity and therefore distracts from it. Games, such as the one by Finkelstein and colleagues [Fin+11], in contrast, have the potential to direct the focus on physical activities consciously and thus exertion and combine these with high enjoyment. Thus, especially this kind of VR exergames can be suitable for a behavioral change, as conscious physical activity is combined with the experience of enjoyment. However, even though there are isolated studies with this kind of VR exergames [Fin+13; Nic+12b; Nic+12a], the main focus of this research area is on VR exergames that use repetitive strenuous movement as an interaction with the game [ML20; Bar+18; Kou+20; Hal+19; Ija+20; Gre+20; KNVA19; Koj+19].

However, using an HMD VR system in particular results in a disadvantage compared to non-VR exergames. Since the HMD is worn close to the head and rests directly on parts of the face, the weight and heat emitted by the HMD can be perceived as disruptive when playing an exergame [Bar+18]. In addition, sweat can accumulate under the glass and be perceived as unhygienic [Sha+15a]. Furthermore, so-called simulator sickness can occur when using VR technology. Simulator sickness is a collection of symptoms that occur when the visual impression does not correspond to the proprioception, especially the sense of balance. If a movement is simulated in a virtual environment, but the player stands on the spot in the real world, the visual impression and the remaining proprioception do not match. The resulting simulator sickness that some people experience describes a feeling of nausea that can have different manifestations such as sweating, headaches, blurred vision [Ken+93]. For exergame development, it is therefore essential to avoid this mismatch of sensory stimuli for the player. Hence the virtual camera should only be moved by corresponding head movements of the player. Room-scale VR is a helpful tool in this regard, as the movement in the virtual environment is realized by one-to-one movements in the physical world, resulting in a match of sensory stimuli. Despite the possible disadvantages of current VR technology, positive effects and a high level of enjoyment can already be achieved with this technology, as presented in this section and the following chapters. In addition, VR systems are constantly being developed further and are becoming more and more usable for exergames. The manufacturers of the most popular VR systems Oculus Quest and HTC Vive, are already advertising the possibilities that their systems offer for physical activities and sports[9], and are even presenting concepts for special HMDs for this purpose[10].

In summary, VR is a promising technology to address the fundamental problems of lack of physical activity and long periods of sedentary behavior. Immersive VR technology can create a high degree of presence, which positively affects the players' enjoyment and intrinsic motivation. Thus, VR exergames can combine physical activity with high enjoyment to address the lack of enjoyment regarding the performance of physical activities. The immersive VR technology and the associated high experience of presence can even increase the effects that non-VR exergames already offer. Further, unlike conventional non-VR video game systems, modern room-scale VR systems are based on an inherent motion paradigm. They use body movements to control the system and are predominantly used while standing. Thus, playing VR games, even without required strenuous movement, represents added value compared to conventional digital games. Thus, despite the potential drawbacks that current VR technology has, VR poses a promising tool to tackle the problem of physical inactivity and sedentary behavior.

[9] `https://www.oculus.com/blog/exercise-by-accident-vr-games-to-help-you-work-out-at-home` last accessed on Nov. 19, 2021

[10] `https://www.theverge.com/circuitbreaker/2021/4/21/22395284/htc-vive-air-leak-fitness-headset-concept-not-real-product` last accessed on Nov. 19, 2021

Chapter 3

Exergaming in Virtual Reality

The underlying idea for using VR in the context of exergames is the high degree of immersion this technology offers and the resulting high level of presence, which can positively affect the players' enjoyment. However, in the presented work [ZPG17; APVA18; Sch+18; YK16; Sha+15b; McD+20] it is noticeable that none of the studies assessed the experience of presence in the context of the relevant constructs enjoyment and (perceived) exertion. Furthermore, all of these studies, except for the study of Finkelstein and colleagues [Fin+11] used a monotonous strenuous activity to control the exergame. Such an activity is based on external devices such as an exercycle or rowing machine. The results of McDonough and colleagues [McD+20] and Zeng and colleagues [ZPG17] suggest a distractive effect for these types of VR exergames. However, these VR exergames do not utilize the potential of modern room-scale VR systems as Finkelstein and colleagues [Fin+11] did. Furthermore, the results of Finkelstein and colleagues' work suggest that VR exergames not distracting from a strenuous movement but instead consciously focusing on it can achieve high enjoyment with a concomitant high perceived exertion. Also, McDonough and colleagues [McD+20] used different games in the VR and non-VR condition, which lowers the understanding of the reported effect of the VR technology. Furthermore, none of the work presented on VR exergames considered embodiment. As presented in Section 2.5.1, embodiment is an influencing factor for the experience of presence. Highly immersive systems can create a stronger sense of embodiment compared to less immersive systems [Wal+18]. However, none of the presented work integrated a virtual body representation of the player. Nonetheless, increased presence through the representation of a realistic virtual body and the accompanying sense of embodiment may positively impact player enjoyment. Kim and colleagues [KPB14] showed in their work that players of a non-VR exergame with a virtual body experienced significantly higher levels of presence, enjoyment, and even physical exertion compared to players without a virtual body. Thus, also for VR exergames, it can be assumed that the visualization of a virtual body representation provides a significant advantage. However, several aspects have to be considered. First, the represented body should resemble the appearance of the user [Wal+18]. Furthermore, as an influencing factor of embodiment, the feeling of agency is mainly determined by visual-motor synchronicity. A movement of the player's body in the real world should accordingly lead to a simultaneous identical change of the virtual body in the virtual world. This synchronicity results from the tracking technology used. This technology can differ between VR and non-VR systems in terms of technical factors such as the sampling rate, accuracy, or latency. In addition to the output device, VR systems thus offer an additional feature with a higher degree of immersion through the technology for the integration and corresponding representation of the body. In the context of body representation, the player's perspective in the game is also essential. A fundamental distinction can be made between a first-person perspective and a third-person perspective. The advantages of the respective perspectives concerning presence are not clear. The work of Denisova and Cairns [DC15] concludes that the experience of presence is higher in the first-person perspective than in the third-person perspective. The work of Kim and colleagues [KPB14] and Gorisse and colleagues [Gor+17] conclude that it is difficult to make a general statement about the experience of presence in the respective perspectives and that a high presence experience is possible in both perspectives. According to the authors, the application scenario is more important. For precise body movements, according to Gorisse and colleagues [Gor+17] the first-person perspective, and for the spatial perception of the virtual environment, the third-person perspective should be preferred.

Thus, it can be summarized that embodiment as an influencing factor for presence and enjoyment in the context of VR exergames has not been considered so far, and potential influencing factors such as perspective or tracking technology have not been investigated. Moreover, none of the previous works have investigated all relevant constructs such as presence, enjoyment, perceived exertion, physical exertion, and embodiment in the context of VR exergaming. Furthermore, only initial qualitative observations have been made on VR exergames that do not use repetitive movements as interaction. For this reason, the following work was developed and evaluated:

Born, F., Abramowski, S., & Masuch, M. (2019, September). Exergaming in VR: The Impact of Immersive Embodiment on Motivation, Performance, and Perceived Exertion. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)* (pp. 1–8). IEEE. DOI: 10.1109/VS-Games.2019.8864579

3.1 Summary

In order to systematically investigate the influence of a VR system, tracking fidelity, and perspective in the context of an exergame, the game *Fit The Shape* was developed. Fit The Shape was developed as a VR exergame that is not based on repetitive

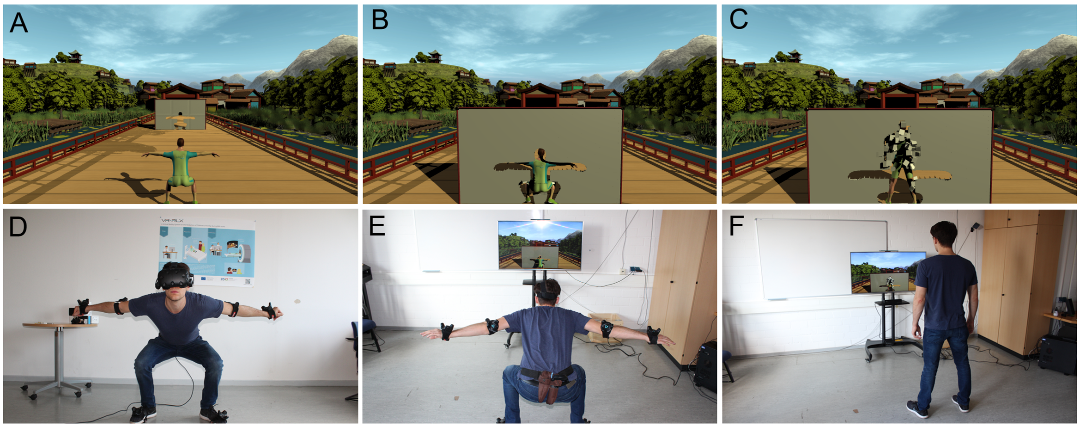

FIGURE 3.1: **(A)** An opening in the form of a squat pose can be seen in the wall coming towards the player. **(B)** If the player gets into the corresponding posture, the virtual body fits into the opening, and there are no contact points with the wall. **(C)** In the event of a collision with the wall, cubes are knocked out of the wall at the contact points. **(D)** The player moves into a squat position in the VR1PP version. The six HTC Vive trackers can be seen on the feet, hands, and elbows. **(E)** The player gets into a squat pose in the Tracker version. The game is played on a 50-inch TV. **(F)** In the Kinect version, no HTC Vive trackers are needed. ©2019 IEEE

movements like cycling or rowing. As shown in Figure 3.1, the player in Fit The Shape is at the end of a long wooden path. A virtual male or female avatar represents the player. At the end of the path, a wall is instantiated every 4.5 seconds and moves toward the player. A specific shape is cut into the wall. The players' task is to move their bodies to fit through the shape in the wall. If parts of the body collide with the wall, small cubes are knocked out of the wall at the point of contact, and the player loses points. The game thus requires balance, coordination, and precise movements. There are a total of ten different wall setups that require different movements. Since the players have only 4.5 seconds to change their pose, the game requires constant unpredictable movements. One game round consists of 40 walls. A total of four different conditions of the same game were developed. The game was initially developed for a conventional TV as the output device. In this version, the player's movements are captured via a Microsoft Kinect and transferred to the virtual avatar, which the player experiences from a third-person perspective. Subsequently, a VR version of the exergame was developed. A wired HTC Vive was used as the output device, and HTC Vive trackers replaced the Kinect. A total of six Vive trackers on the hands, feet, and elbows and a controller on the pelvis were used to track the player's key points. With these tracking points and the HMD, the entire body motion was approximated using inverse kinematics. The VR version of the game was developed in two versions, differing in terms of perspective (first vs. third), as shown in Figure 3.2. In addition, to investigate the influence of tracking technology, in a fourth version of the game, in the non-VR variant, the

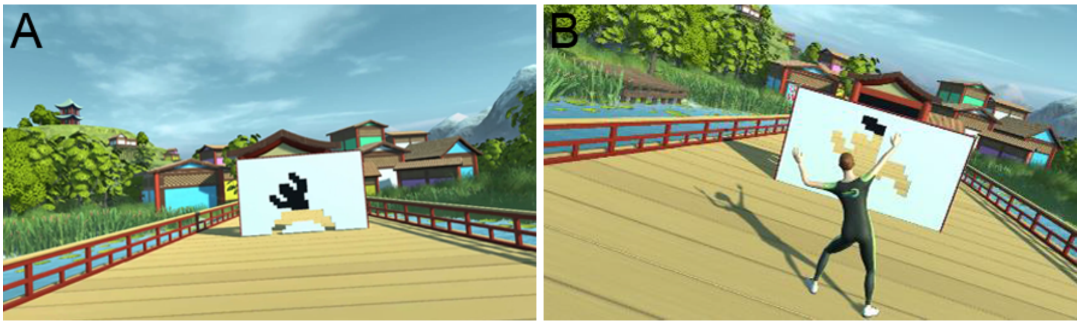

FIGURE 3.2: **(A)** A challenging pose must be taken in the VR1PP version of the game. **(B)** A similar pose must be taken in the VR3PP condition. In this screenshot, the player is represented by a female avatar. In both versions, an HMD is used as the output device, so the camera's rotation depends on the rotation of the player's head. ©2019 IEEE

TABLE 3.1: The four versions of Fit The Shape as a function of the output device, tracking device, and perspective.

Version	Output Device	Tracking Device	Perspective
VR1PP	HTC Vive	Vive Tracker	First-Person
VR3PP	HTC Vive	Vive Tracker	Third-Person
Tracker	50-inch TV Screen	Vive Tracker	Third-Person
Kinect	50-inch TV Screen	Kinect	Third-Person

Kinect was replaced by HTC Vive trackers. This involved placing an additional tracker on the player's head, as no HMD was used in this version. The HTC Vive offers a higher degree of immersion compared to a conventional screen due to its technical properties presented in Section 2.5.1. The HTC Vive trackers offer a higher degree of immersion due to the higher sampling frequency of 120 Hz in contrast to the 30 Hz of the Kinect, which results in much smoother movements of the virtual body representation. The four versions of the game are summarized in Table 3.1.

A quantitative evaluation was conducted following the development of the game. Enjoyment (IMI), presence (IPQ), heart rate (%HR), and perceived exertion (BORG) were recorded. In addition, analogous to the work of Mestre and colleagues [MEM11] presented in Section 2.6, the associative focus was recorded. This construct describes the player's attentional focus on external stimuli (dissociation) or internal body stimuli (association). In addition, player performance was calculated based on the amount of cubes knocked out of the wall when they collided with the body. Players' embodiment was assessed analogously to Galvan Debarba and colleagues' study [GD+17] with a total of six questions. Thirty-two female and twelve male subjects participated in the evaluation. The evaluation was conducted in a within-subjects design; hence, each subject played each version of the game in random order. The results of the study reveal a dichotomy. Thus, for presence, embodiment, enjoyment, and performance, significantly higher scores could be observed in both VR versions of the game compared to both non-VR versions. Moreover, for the general presence and spatial presence subscales of the IPQ and the body ownership and self-location subscales of the embodiment questionnaire, even higher scores could be observed in the VR1PP condition in contrast to the VR3PP condition. Analysis of dissociation and association scores showed that players in all versions reported a focus more related to internal body stimuli. This focus was even more associative in the VR conditions than in the non-VR conditions. The classification of %HR showed that a medium intensity level was achieved in all conditions. Comparing the normalized BORG values and %HR showed no significant difference between groups. Thus, using a VR system did not significantly reduce perceived exertion. Further, there was no significant difference between the non-VR conditions for any of the assessed constructs, indicating that the tracking fidelity had no significant impact.

Chapter 4

Increasing the Exertion

Exergames offer a wide range of benefits and have already been used and evaluated in several different application contexts with positive effects, as outlined in Section 2.4.2. However, concerning physical exertion or intensity levels, there are mixed findings. On the one hand, studies have observed similar or even greater exertion levels in players of exergames compared to conventional physical activity [Gao+15; GM12; RWB09; War+07]. On the other hand, the opposite conclusion that exergames cannot achieve the same level of exertion as conventional physical activity was drawn in other works [Kar17; GZS13; McD+18; Per+19; Gra+07]. In particular, the respective exergames used in the studies are crucial and can differ, sometimes greatly, in terms of the exertion required. Thus, Graves and colleagues [Gra+07] showed that none of the Wii Sports games could generate an intensity level that would contribute to the daily required amount of physical activity. Moreover, conventional exergames such as Wii Fit or Wii Sports have a fundamental limitation in the maximum achievable activity level [Miy+10]. Also for popular VR (exer)games like Longbow from The Lab [Val16], Beatsaber [Gam19], Holopoint [AS16] or Hot Squat [Gam16] it could be observed that none of the games generate a vigorous activity level [Per+19; Eva+21]. Even beyond, only Hot Squat can generate a moderate intensity level [Eva+21]. Hence, the question of how the exertion in an exergame can be increased arises. In theory, the required physical movements could simply be designed more exerting. As shown by the work of Perrin and colleagues [Per+19], carrying weights attached to the players' arms or performing extra movements not required by the original game as in the work of Mondero and colleagues [Mon+14] can increase the exertion artificially. While these approaches have a positive effect on required exertion, they were not considered by the authors in the context of player enjoyment. However, as shown in Section 2.4.2, an increase in perceived exertion can reduce player enjoyment [ARK94; HR89; EHP08; EPP11]. Especially in the context of VR exergames not relying on repetitive exertive movement for interaction, the relationship between perceived exertion and enjoyment is relevant. As discussed in the work of Finkelstein and colleagues [Fin+11] and also in the paper [BAM19] presented in the last chapter, VR does not distract from the exertion in this type of exergames but instead focuses it through a strengthened associative focus [BAM19].

Thus, it is crucial to find a suitable mechanism to compensate for a potential loss of motivation due to increased exertion.

A first approach to this was already presented in Section 2.4.2 by the work of Ketcheson and colleagues [KYG15]. In this work, in addition to playing the game, players could unlock power-ups in a game through additional exertion generated via an exercycle when their heart rate exceeded a specific predefined value. However, even though this mechanism was perceived as enjoying, the authors did not investigate the statistical impact on enjoyment. In addition, the extra exertion is based on a device that requires repetitive movements and thus cannot be integrated into a room-scale VR exergame. For increasing the exertion in a room-scale VR exergame, the requirement to find a mechanic that can be integrated into the gameplay and is not based on a static device such as an exercycle or rowing machine thus arises. Furthermore, the chosen mechanic should have a motivating character in addition to increasing the exertion, compensating for a potential loss of motivation due to the increased exertion. One way to achieve this is by using passive haptics and the resulting haptic feedback. Passive haptics describes real physical objects that also exist in the same form in the virtual world and can thus be touched by the player and thereby provide haptic feedback [LSH99; Ins01]. A table that exists in the same place in the virtual and real world and can thus be touched by the player is an example of a passive haptic object. Insko [Ins01] was able to show that the integration of passive haptics can add a significant benefit to the presence experience in VR. The haptic feedback that a player experiences can be divided into two different types: tactile and kinesthetic feedback. Tactile feedback describes the sensation of touch perceived through the skin. Kinesthetic feedback describes a force acting on the body measured by muscles or sensory cells [Ram+06].

Also in exergames, the integration of haptic feedback can have an enhancing effect. As shown in Section 2.4.2, Stach and Graham [SG11] showed that adjusting the pedaling resistance of an exergame depending on the virtually displayed surface condition could increase the perceived realism and enjoyment. The impact of haptic feedback on players has also been demonstrated for VR exergames through the work of Shaw and colleagues [Sha+17]. In their work, the authors used a fan to suggest the headwind that the player would experience by riding the exercycle, thus enabling tactile feedback. In addition, kinesthetic feedback was implemented by adjusting pedal resistance, which was altered by various events in the game. Both feedback variants were able to increase the presence experience of the players significantly. Furthermore, the tactile version could even increase the players' enjoyment. Interestingly, the kinesthetic feedback version increased presence but not enjoyment, but significantly increased players' exertion. However, since the authors did not measure the perceived exertion, it is difficult to conclude the relationship between enjoyment, exertion, and presence. In addition, Barmpoutis and colleagues

FIGURE 4.1: **(A)** shows the real broom used as a controller for Ghost Sweeper. **(B)** shows the virtual broom counterpart in Ghost Sweeper. ©2020 IEEE

[Bar+20] showed in their work that in a VR kayak simulation played in a seated position with an Oculus Rift, a real paddle as a controller in contrast to the standard Oculus Rift controllers could significantly increase the enjoyment of the players.

These works show that the integration of haptic feedback can significantly enhance exergames. Thus, the use of passive haptics and the resulting haptic feedback represents a possibility to increase exertion and presence simultaneously and thus enjoyment. Hence, increased presence could counteract a reduction in enjoyment due to increased exertion. Thus, an increase in exertion without reducing enjoyment would be possible. To investigate this outlined possibility in the context of a room-scale VR exergame, the following work was developed and evaluated:

Born, F., Masuch, M., & Hahn, A. (2020, August). Ghost Sweeper: Using a Heavy Passive Haptic Controller to Enhance a Room-Scale VR Exergame. (Best Paper Nomination) In *2020 IEEE Conference on Games (CoG)* (pp. 221–228). IEEE. DOI: 10.1109/CoG47356.2020.9231867

4.1 Summary

To investigate the use of haptic feedback to increase exertion in a room-scale VR exergame, the game Ghost Sweeper was developed for the HTC Vive. The player is

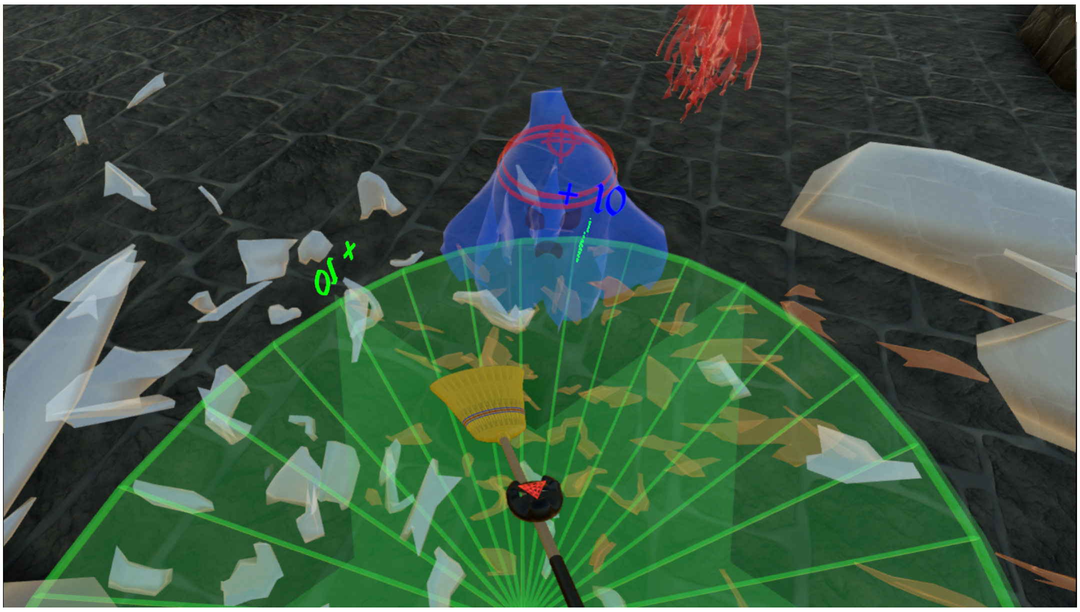

FIGURE 4.2: Several ghosts approach the player, who just destroyed one ghost with the broom controller in Ghost Sweeper. ©2020 IEEE

placed in a medieval castle haunted by countless ghosts in the game. The player's task is to defeat as many ghosts as possible in three minutes. The HTC Vive's standard controller was replaced with a broom, as shown in Figure 4.1. The broom handle was wrapped with grip tape to provide a better grip. An HTC Vive tracker was attached to the broom's center using a clamp integrating the broom as an interaction object in the VR game. The broom has a length of 135 cm and weighs 594 g with the clamp and the HTC Vive tracker attached, twice as heavy as a conventional tennis racket. A virtual broom model was then created for the VR exergame that resembles the real broom.

In Ghost Sweeper, new ghosts are permanently generated, moving towards the player. The player has to defeat the ghosts by hitting them with the broom. Below the player, a green circle is placed on the floor, as shown in Figure 4.2. A ghost can only be destroyed if the player first hits through the ghost and then onto the green area. Thus, it can be ensured that the player hits the floor with the broom in the real world and receives kinesthetic feedback. There are different types of ghosts that can withstand differing numbers of hits and award different points to the player when destroyed. The spawn rate of the ghosts is so high that the player has to interact with the broom non-stop for 3 minutes without pausing. The game is thus intended to be a short, high-intensity workout.

The broom was chosen as an interaction object because, unlike other objects such as tennis rackets or baseball bats, it cannot cause significant damage. In addition, we wanted to use an everyday object to show that a complex setup is not necessary to increase the exertion of an exergame. Since the broom is a passive haptic object,

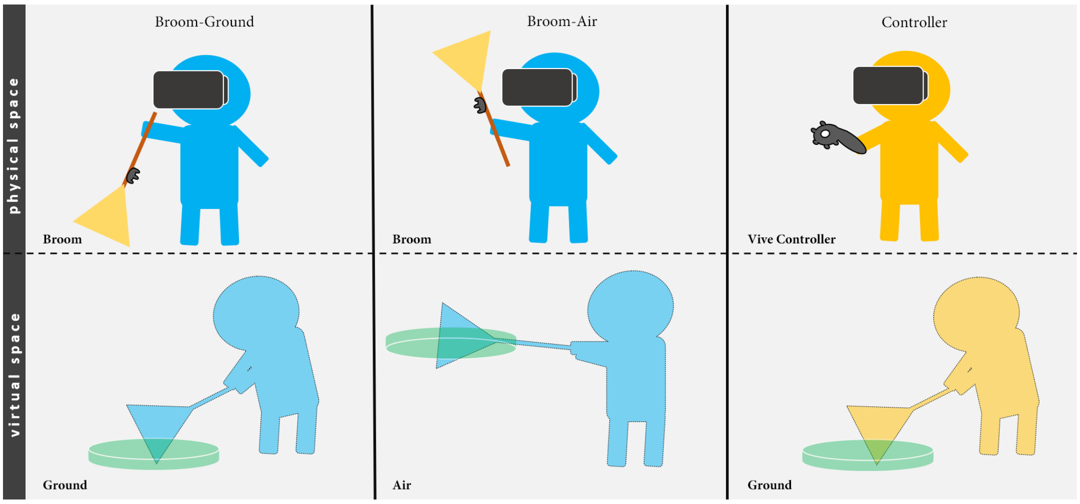

FIGURE 4.3: Study conditions of Ghost Sweeper. ©2020 IEEE

it generates tactile feedback when it is touched. In addition, kinesthetic feedback is generated when the broom is hit on the ground. To systematically investigate the influence of the broom as an interaction object, two other versions of the game were created. The ghosts and the green floor were moved up half a meter in a second condition. Thus, in this condition, the players no longer have to hit the ground with the broom and thus do not receive the respective kinesthetic feedback. The third condition consisted of a control condition in which the broom was replaced with the standard HTC Vive controller. However, the virtual broom representation was still used in the control condition. Through these three conditions, the influence of the broom and the kinesthetic feedback from hitting the ground can be evaluated. The conditions are shown in Figure 4.3.

Following the development of the game versions, a quantitative evaluation was conducted. This involved measuring players' enjoyment (IMI), presence (IPQ), perceived exertion (BORG), and, as in the paper presented in the previous chapter, associative focus. In addition, physical exertion was measured as an increase in heart rate between the average heart rate during a resting period measured at the beginning of the evaluation and the average heart rate during gameplay. Sixty-nine female and 13 male subjects participated in the study. The study was conducted in a between-subjects design. Thus, each subject tested only one of the versions. A wireless HTC Vive was used in the study. The results of the study show that both game versions with the broom were able to increase the heart rate significantly more than the control condition. Even though there is no statistical difference between the two broom conditions in terms of increase in exertion, the classification of %HR shows that in the Broom-Ground condition, 60% of the subjects reached a moderate or vigorous exertion level, whereas this is only 30% in the Broom-Air condition and 22% in the Control condition. Perceived exertion showed a similar trend to physical exertion and was significantly higher in both broom conditions than in the control condition. Moreover, the comparison of %HR and the relative BORG values showed no significant difference. Thus, the increase in physical exertion was perceived accordingly. Moreover, both Broom conditions showed a significantly higher associative focus than the control condition. Regarding enjoyment, high values could be observed in all conditions. However, these values did not differ significantly from each other. Despite the higher exertion in the broom condition, there was no reduction in enjoyment in the two broom conditions. Interestingly, however, significantly higher values could be observed in both broom conditions compared to the control condition concerning the pressure/tension subscale of the IMI. This subscale is a negative predictor of enjoyment. Regarding presence, significantly higher scores were found only for the involvement subscale in the Broom-Ground condition than the other two conditions. However, beyond that, a strong correlation was found between the presence and enjoyment of the players. Furthermore, the investigation of the participants' regular physical activity as a potential factor influencing the findings did not yield a significant result.

Chapter 5

Multi-User Room-Scale VR

The previous chapters have specifically explored the player's presence experience as a central aspect in the context of exergames. As shown in Section 2.3, the experience of presence in the context of digital games is an influencing factor for the enjoyment of the players. In addition, however, the satisfaction of the basic needs for autonomy, competence, and relatedness is crucial for the emergence of intrinsic motivation and the long-term pursuit of an activity. Digital games can uniquely satisfy these three basic needs and thus have a high intrinsic motivation potential. However, relatedness as a basic need is a less studied construct in the literature, although over 70% of digital game players play these games in a social context, such as online or at the same physical place [GLE14]. The influence that relatedness or social settings can have is also evident in the context of exergames. Staiano and colleagues [SAC12] observed overweight adults playing the Wii exergame EA Sports Active [Can09] in a six-month exergame intervention. In this intervention, participants played the exergame in either a cooperative or competitive mode for the entire period. The authors observed that the main factor influencing interest and involvement in the exergame was the social cohesion and friendship established during the intervention. In addition, the authors could observe that the subjects who played in the cooperative condition showed significantly higher enjoyment. Paw and colleagues [Paw+08] observed that children aged 9 – 12 years played twice as much in a multiplayer condition than children in a single-player variant during an exergame intervention over 12 weeks that included a dance game. In addition, participants' dropout was significantly lower in the multiplayer condition. In addition, Peng and Crouse [PC13] evaluated the exergame Kinect Adventures! [Stu10] in their work with 162 subjects in three different conditions. In a control condition, subjects played alone. In a cooperative condition, two subjects played toward a common goal while being in the same room. In a competitive condition, two participants played against each other in separate rooms. The authors observed that both multiplayer variants significantly increased the players' enjoyment and future game-play motivation compared to the single-player variant. However, the multiplayer variants did not differ in the constructs. The authors also observed that the cooperative variant led to significantly less physical exertion than the single-player variant in the same room. The competitive variant in separated rooms did not show this significant reduction. However, because the authors changed two variables between each of the multiplayer conditions, it is difficult to attribute the reduction in exertion to the cooperative mode or playing in shared or separate spaces. Furthermore, the review by Marker and Staiano [MS15] concludes that cooperative exergames can significantly enhance enjoyment over competitive ones. The studies show that social settings can have a significant benefit for exergames. Of particular interest is the perception of social presence, which was introduced in Section 2.5.1. In the context of digital games, social presence has a significant impact on players' enjoyment [GDKI08b] and, analogous to spatial presence, also has a positive impact in the context of exergames concerning constructs such as general exercise intention [WLT15] or enjoyment [KT16]. Based on the work of Peng and Crouse [PC13], however, the question arises as to whether playing in a shared room or two separate rooms is more beneficial.

Gajadhar and colleagues [GDKI08b] studied the impact of playing a digital game together in the same room compared to playing the same game in two separated rooms. The authors observed that playing in the same room significantly increased social presence and enjoyment. If these findings are now transferred to a room-scale VR setting, the question arises whether the masking of the real world and the simultaneous presentation of virtual content and thus a suggestion of a co-player's physical presence equalize the benefits of the actual physical presence of another player. An initial answer to this question is provided by Gómez and Verbeek's study [GV16]. In their work, the authors observed no difference in social presence in a seated cardboard VR game when two players play in the same room or two separate rooms. However, an additional problem arises in a room-scale VR setting: multiple players' simultaneous use of the same physical room can lead to collisions among players. Masking the real world through the use of HMDs can be a potential source of interference for collisions [Lac+17]. In their work, Podkosova and Kaufmann [PK18] investigated a remote and co-located setting in a room-scale VR application for two users. Both users had to solve a navigation task and move through a room simultaneously. The authors observed that the co-located setting changed the users' behavior in terms of the paths they chose and the speed at which they moved and that the users' focus shifted from the task of the application to collision avoidance. In the context of a simple navigation task and deliberately provoked collision, the results of Podkosova and Kaufmann are comprehensible. However, if these results are transferred to a room-scale VR game, the question arises what influence the physical presence of another person has. Of particular interest here is the influence on social presence, which was not examined in Podkosova and Kaufmann's work. To investigate the social presence and other relevant constructs in the context of multiplayer room-scale VR between a co-located and remote setting, the

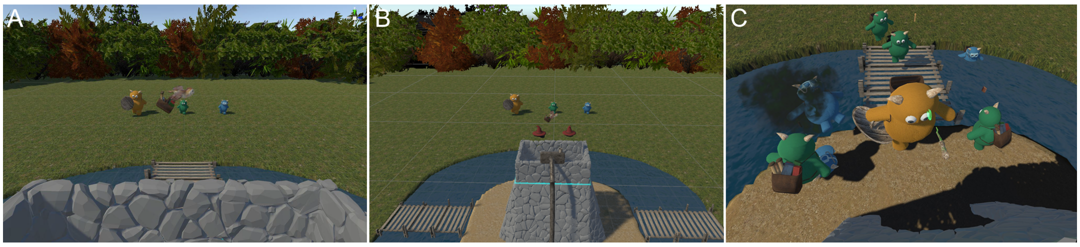

FIGURE 5.1: **(A)** Three different enemies approach the tower from the perspective of a player **(B)**. The tower is surrounded by a trench, which only the blue enemies can pass. The others have to cross over the bridges. **(C)** A player's perspective during the actual game shows several enemies approaching the tower to steal books. ©2019 IEEE

following work was developed and evaluated:

Born, F., Sykownik, P., & Masuch, M. (2019, August). Co-Located vs. Remote Gameplay: The Role of Physical Co-Presence in Multiplayer Room-Scale VR. In *2019 IEEE Conference on Games (CoG)* (pp. 1–8). IEEE. DOI: 10.1109/CIG.2019.8848001

5.1 Summary

In order to investigate a multiplayer room-scale VR game, a cooperative testbed game for two players was developed first. In the game, the players are located on top of a tower, as shown in Figure 5.1. Both players take the role of wizards in the game. They are each represented by a hat and an HMD, indicating where they stand and look at. In addition, both players carry a magic wand in one of their hands. The size of the base area of the tower corresponds to the actual walkable area in real space. The players' task is to eliminate monsters running towards the tower. If the monsters reach the tower, they steal valuable books and run back to the adjacent forest. There are different types of monsters, which differ in their abilities, health points, and speeds. Using the wand, which an HTC Vive controller controls, players can fire a shot at the monsters by pressing the trigger button. The shooting power is quintupled if both players focus on the same monster with one shot. In addition, both players can use an additional mechanism to create a powerful thunder cloud and detonate it to eliminate multiple monsters at once. Since the monsters attack the tower from multiple sides simultaneously, the players must constantly communicate and coordinate their attacks to defend the tower. A game round lasts 9 minutes and includes 193 monsters, independent of the players' performance. Two versions of the game have been developed, differing only in the physical presence of the co-player. In the co-located space condition, both players are in the same room. In

FIGURE 5.2: The setup in the remote version of the game. The area in the right room marked out with tape corresponds to the walkable play area in the left room. ©2019 IEEE

the remote space condition, both players are in separate rooms, as shown in Figure 5.2. The walkable area is identical in both spaces. Since each HMD is connected to a separate PC in both versions of the game, and the game information between the players must therefore be synchronized via a network connection regardless of the version, the game design did not have to be changed or technically adapted between the two versions. The VR system used for both players in both conditions was a wired HTC Vive. In both versions, the players wore a headset and communicated via Discord.

A quantitative evaluation followed the development of the game. Spatial presence was measured using the IPQ. Social presence was measured using the cooperative social presence sub-scale of the competitive and cooperative presence in gaming questionnaire [HC14]. In addition, the quality of communication was measured by five self-formulated items. The quantity of communication was captured via corresponding statistics from Discord. In addition, three questions were asked about perceived freedom of movement and conscious collision avoidance. Performance was derived from the game based on monsters defeated and books stolen. Eighty-eight subjects (40 female, 29 male, 19 gave no answer) participated in the study in a between-subjects design. There were no differences between conditions concerning spatial presence. Social presence, on the other hand, differed significantly between conditions. Subjects in the remote space setting showed significantly higher social presence scores than those in the co-located setting. Furthermore, this tendency was also evident for in-game performance. The players in the remote setting could defeat significantly more monsters than in the co-located setting. The rated quality of communication was also significantly higher in the remote setting than in the co-located setting. Regarding the other constructs, no difference between the settings could be observed. Interestingly, this also includes the questions regarding collision avoidance or perceived freedom of movement. The results suggest that players in both versions were quite aware of where the teammate was but felt little restriction on their freedom of movement and did not consciously focus on collision avoidance. Furthermore, positive correlations could be observed between the level of familiarity of the players and various constructs such as the social presence or communication quality. However, considering the degree of familiarity, analyses of covariance did not show any deviation from the original findings, suggesting that the degree of familiarity had no significant influence on the observed findings.

Chapter 6

Voluntary Exertion and Virtual Performance Augmentation

The studies presented in Section 2.6 and the findings from the paper summarized in Chapter 3 suggest that VR exergames can offer a significant advantage over non-VR exergames. In the introduction to the paper presented in Chapter 4, the problem of exergames often not achieving a similar activity level compared to conventional physical activity, although having an inherit exerting property, was shown. Thus, exergames often cannot contribute to the WHO's recommended amount of exercise [Gra+07]. The work from the paper [BMH20] presented in Chapter 4 is a first approach to focus the increase of exertion in a VR exergame. However, it is noticeable that in this work, as well as in other works investigating the motivational influence of different mechanisms in exergames, players in the studies were not offered the choice to perform the exerting activity voluntarily [BMH20; Bar+18; Ioa+19]. Playing and thus progressing in the exergame was inseparably linked to performing the strenuous activity. Although high enjoyment values have been observed in the mentioned studies, the tasks in the studies required the subjects to test the respective game version of the exergame. However, in the context of intrinsic motivation, this approach represents a potential negative influence concerning player autonomy. This raises the question of what would result from decoupling the strenuous activity from the control and progression of the game. Not only could player autonomy and thus intrinsic motivation be increased, but also this separation would allow an isolated investigation of the mechanism and its actual motivational potential. Especially concerning increasing the exertion, a statement could thus be made about the potential of a mechanism for its integration into an exergame. For example, suppose a strenuous voluntary activity is performed. In that case, although this activity is not relevant for the actual game, the motivational appeal of the mechanism is so great that the activity is performed despite the negative relationship between perceived exertion and enjoyment. In the work of Ketcheson and colleagues [KYG15] presented in Section 2.4.2, such an approach was taken. Players could earn additional power-ups in an exergame when their heart rate reached a predefined level.

An exercycle served as the strenuous interaction. However, the game was also controlled via the exercycle, not properly separating between the interaction with the game and the additional strenuous interaction. Nevertheless, the authors observed that this power-up mechanism could lead to greater exertion and high enjoyment. However, no detailed inferential statistical evaluation was performed.

For motivating players to engage in voluntary exertion, the incentive with which the player is rewarded for performing an optional strenuous activity is essential. Especially in the context of a room-scale VR exergame, the question arises of which mechanism can be used for the approach to voluntary exertion. One possibility is the so-called virtual performance augmentation (VPA) [Ioa+19]. VPA is based on the idea that VR systems enable an exact transfer of body movements to a virtual avatar. If the effects of the body interactions are then amplified in the virtual environment, a sense of empowerment and thus an increase in intrinsic motivation can result, according to Ioannou and colleagues [Ioa+19]. In VR applications and exergames, VPA has already been shown to have a positive influence on enjoyment through the exaggerated representation of virtual kicks [Gra+18], running speeds [Ioa+19], and jumping heights [Ioa+19; Wol+20]. Based on these findings, the question arises whether VPA is suitable as a mechanic to motivate players to engage in an optional strenuous activity in a room-scale VR exergame. To answer this question, the following work was developed:

Born, F., Rygula, A., & Masuch, M. (2021, September). Motivating Players to Perform an Optional Strenuous Activity in a Virtual Reality Exergame Using Virtual Performance Augmentation. In *Proceedings of the ACM on Human-Computer Interaction, 5.* CHI PLAY (2021). (pp. 1–21). DOI: 10.1145/3474652

6.1 Summary

In order to enable voluntary exertion in a room-scale VR exergame, the first step was to develop a controller that enables optional exertion-based interaction. In a room-scale VR exergame, the fundamental limitation arises that, unlike Ketcheson and colleagues [KYG15], a stationary device such as an exercycle or rowing machine cannot be used beneficially. Instead, a device that would not affect the main interaction of the game but could be interacted with at any point is required. Based on these prerequisites, a novel controller was developed, which can be seen in Figure 6.1. The basis for the controller is a grip strength trainer, where the strength to press it together completely is freely adjustable from 20 kg to 40 kg traction resistance equivalent. A FlexiForce pressure sensor and a 3D-printed grip shell were mounted on one of the handles to measure the pressure the player exerts on the grip strength trainer. The necessary technology to receive and process the pressure values and

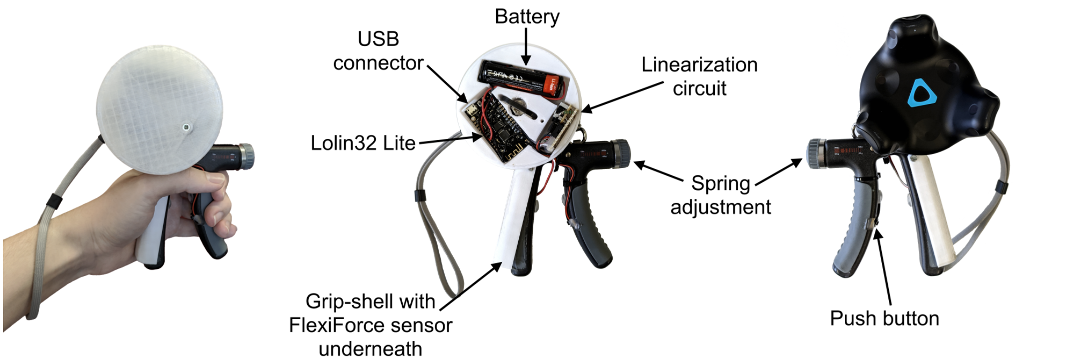

FIGURE 6.1: The controller developed for Grip It.

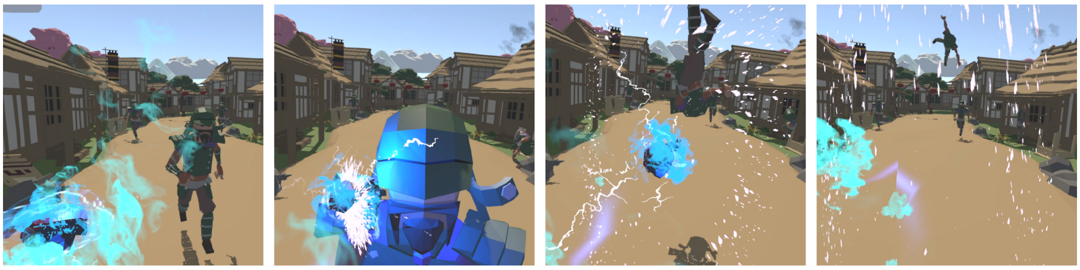

FIGURE 6.2: Enemies are running towards the player in the VPA condition in the game Grip It. The player has reached the highest VPA level and thus knocks the opponent away over a long distance.

send them to a receiver via Bluetooth was integrated into a self-designed and 3D-printed case. This case was attached to the controller using a 1/4 inch screw. On the other side of this screw, an HTC Vive tracker can be attached so that the controller can be used in a VR environment. Two identical controllers were created to transfer both players' hands into the game. The game Grip It was developed to enable an optional strenuous interaction based on this controller. In this game, the player is located in a Japanese village from the feudal period. As shown in Figure 6.2, the player is attacked by numerous enemies. The player's task is to defeat the enemies, thus protecting the village. The player can defeat an enemy by hitting the enemy's head with a punching motion. The punching motion must have a minimum speed similar to a punch in the real world to defeat an enemy. There are different types of enemies, which differ in the number of hits they can withstand. A game round lasts about five minutes and always includes the same number of enemies. The player is represented by only two hands. The position and rotation of the hands are based on the Vive trackers attached to the controllers.

However, parallel to playing the game, the player can press the controllers together. For this work pressing the controller together and holding it in that position was chosen as an optional strenuous interaction. A VPA mechanism was subsequently integrated into the game to motivate players to engage in this optional

FIGURE 6.3: Representation of the enemies' trajectories at three different VPA levels (cyan, yellow, red). The actual trajectories of the enemies are even more exaggerated but adapted here to fit in one figure.

strenuous activity. The longer the controllers are pressed together, the higher the player's VPA level and thus the visualized punch strength. If the controller is not pressed together, enemies just fall to the ground when defeated. If the controller is pressed together for at least ten seconds, the player has reached maximum punch strength, and the enemies are hurled away a great distance, as shown in Figures 6.2 and 6.3. Various visual effects underline the current VPA level and thus the player's strength. The player's punch strength does not influence the actual goal of the game since the numbers of hits necessary to defeat an enemy do not depend on the VPA level. Thus, pressing the controller together is wholly decoupled from progressing in the game. If the players release their grip, the VPA value decreases three times as fast as it increases. A second version of the game was subsequently developed to investigate this VPA mechanism in terms of its motivational potential and compare it against other prominent mechanisms. The player's stroke strength is fixed in this version and cannot be changed. Instead, the player receives points for pressing the controller together, displayed centrally in the game. Points represent one of the most established incentives in digital games and can be implemented as a reward, challenge, or direct feedback depending on the context [RRR15]. A third version of the game was developed as a control condition in which pressing the controllers together has no effect. Also in this version, the punch strength is fixed at the same level as in the points version of the game. The control condition allows making a statement on the motivational character of the controller independent of a motivational incentive.

A quantitative evaluation followed the development of the game. Objective performance and exertion were measured by the amount of time the controllers were pressed together. In addition, since playtime may differ minimally between subjects, the percentage of playtime in which the controllers were squeezed was calculated. In addition, perceived exertion (BORG), presence (IPQ), motivation (IMI), and also, as in the papers from Chapters 3 and 4, the attentional focus were recorded. In addition, all participants in all conditions were asked an open-ended question regarding their motivation for pressing the controller together. A wireless HTC Vive was used for the study. The force required to squeeze the controllers was adjusted to each subject's grip strength at the beginning of the study. 22 female and 25 male subjects participated in the study. The study was conducted in a between-subjects design. Analysis of the percentage and absolute time the controllers were pressed together showed a significant difference between the groups. Subjects in the VPA condition pressed the controllers significantly longer compared to both other conditions. Thus, the VPA mechanism had a greater motivational incentive to perform the strenuous activity. On the other hand, analysis of perceived exertion showed somewhat hard exertion in all conditions but no significant difference between groups. Despite the significantly longer period of pressing the controller together in the VPA condition, this additional exertion did not show up in the BORG scores. Players' attentional focus was strongly associative and did not differ between groups. Players' enjoyment was very high in all conditions and showed no difference between groups. Presence scores were also very high in all conditions but showed no difference between groups except for the experienced realism subscale in which the players in the VPA condition reported significantly higher scores than players in the Points condition. Regarding the individual motivation to press the controller together, the motive to increase the strength of the punches is most dominant in the VPA condition. In addition, however, it is shown in all groups that authenticity is another main motive to press the controllers together. Here, authenticity refers to the fact that a punching motion with a fist seems more realistic than with an open hand. In the context of the game, the controller thus has an inherent appealing character even without an additional incentive.

Chapter 7

Arousal, Cognitive Performance, and Player Experience

In the previous chapters, room-scale VR games and exergames have been considered in terms of various constructs related to PX, especially player motivation. However, beyond the benefits that exergames have in terms of physical activity and motivation, exergames can also be beneficial for other domains, as illustrated in Section 2.4.2. One of these areas is the improvement of cognitive performance [GM12; AH+12]. Cognitive performance includes a variety of "mental processes involved in the acquisition of knowledge, manipulation of information, and reasoning. Cognitive functions include the domains of perception, memory, learning, attention, decision making, and language abilities" [Kie14, p. 975]. The beneficial effect of physical activity on cognitive performance has already been demonstrated in multiple works for a wide range of target groups, different activities, periods, and intensities [Cha+12]. However, physical activity does not directly affect a person's cognitive performance. Rather, physical activity affects a person's arousal, which in turn has a direct effect on cognitive performance [LT10]. Arousal is defined as one of the three dimensions of emotions, along with dominance and valence, and describes the degree of excitation of an affective state, ranging from relaxed to excited [BL94; Rus80; Meh70]. Nevertheless, physical activity is not the only factor influencing arousal. Arousal can furthermore be increased from affective stimuli such as sounds [Bra+99], pictures [Lan05], or game elements [Mog+16].

Based on this, Gao and Mandryk [GM12] investigated whether an exergame can increase arousal and cognitive performance compared to a physical activity that is not integrated into an exergame and compared to a game that is played in a sitting position. The authors chose an activity that could elicit the same activity level in the exergame and the conventional physical activity. However, the authors observed that the exergame could significantly increase the players' arousal compared to both other versions. The participants' cognitive performance in the exergame condition was significantly higher than that of the participants who played the game sitting in front of the PC but was not significantly different from those in the conventional physical activity condition. Beyond the work of Gao and Mandryk, Anderson and colleagues [AH+12] compared a three-month exergaming intervention with a non-gamified version of the same athletic exercise. The authors observed that physical exertion did not differ significantly between the groups. In addition, the authors found that the cognitive performance of the participants in the exergame condition improved significantly. However, unlike Gao and Mandryk, the authors did not survey the participants' arousal in the study. Based on the results of Gao and Mandryk, however, it can be assumed for the results of Anderson and colleagues [AH+12] that the significant improvement in cognitive performance at the same activity level is caused by an increase in arousal in the exergame condition. Based on this finding, the question arises whether arousal and cognitive performance can be further increased in exergames. Since the relationship between arousal and cognitive performance is not linear but follows an inverted U shape [YD+08], cognitive performance decreases after a certain point when arousal increases.

One way to increase arousal in the context of exergames is through VR technology. For digital games, the use of VR can increase the arousal level [Est+14; CT94; PPM19]. Thus, for exergames, VR technology could be beneficial for arousal and thus cognitive performance in addition to the motivational benefits already outlined. However, the use of VR exergames to improve cognitive performance has been investigated in only a few studies so far. Sanudo and colleagues [Sañ+20] observed that training on an exercycle with a Samsung Gear VR leads to better cognitive performance than conventional training on the exercycle without game elements. Li and colleagues [Li+20] observed that after a 4-week VR exergame intervention using the HTC Vive and a self-developed exergame, participants in the VR exergame condition had significantly higher cognitive performance than participants in a control group who did not attend any intervention. However, neither study elaborated on the advantage of VR but compared a VR exergame to conventional exercise or no intervention. The comparison of a VR and non-VR exergame has only been conducted in the study by Huang [Hua20]. After a four-week VR exergame intervention with the Oculus Rift, the authors observed that participants showed higher cognitive performance than participants who participated in a non-VR exergame intervention. In both versions, this involved playing the game Fruit Ninja [Hal10] either in VR or in front of a conventional monitor. However, all participants were over 50 years of age, and the authors did not record arousal or physical exertion. Thus, it is difficult to determine whether the increased cognitive performance was due to increased arousal from VR technology. Similar to the work of Xu and colleagues [Xu+20], the use of VR technology may also have increased physical exertion and thus improved cognitive performance.

In order to investigate the influence of VR on cognitive performance in the context of an exergame and consider different factors such as arousal or physical exertion, the following work was developed. Beyond cognitive performance, this work was also developed to investigate the influence of VR for motivation and

FIGURE 7.1: An overview of the testbed game. ©2021 IEEE

related constructs, complementing the findings of the paper [BAM19] presented in Chapter 3. Thus, the results of this paper serve to support understanding of which aspects VR can provide benefits for in the context of exergaming.

Born, F., Graf, L., & Masuch, M. (2021, August). Exergaming: The Impact of Virtual Reality on Cognitive Performance and Player Experience. (Best Paper Nomination) In *2021 IEEE Conference on Games (CoG)* (pp. 1–8). IEEE. DOI: 10.1109/CoG52621.2021.9619105

7.1 Summary

In order to investigate the impact of VR on arousal, cognitive performance, and various PX-related variables, a testbed game that incorporates identical gameplay regardless of the output device was developed first. As shown in Figure 7.1, in the game, the player is located in a medieval village that Vikings have plundered. The player's task is to defeat the Vikings running from the village back to their ship. Therefore, the player is equipped with a shield and a sword and plays the game in a first-person perspective. An enemy can be defeated with one sword strike. If an enemy is not hit, it runs past the player and jumps into a boat located in the player's back. The shield can be used to block projectiles that are shot at the player from various positions in the village. As shown in Figure 7.2, the shield and sword are controlled by corresponding replicas in the real world. For both items, foam replicas were used, to each of which an HTC Vive tracker was attached. Based on the findings from the paper [BMH20] presented in Chapter 4, it was intended to increase exertion without reducing player enjoyment by using heavy passive haptic controllers. In addition, the possible interactions in the VR game are reduced because a

FIGURE 7.2: The sword is 16 cm wide, 71 cm long, and weighs 356 g, including the HTC Vive Tracker. The shield is 50 cm in diameter and weighs 829 g, with the mount and HTC Vive Tracker included. While the sword is held in hand, the back of the shield has a mount for the entire forearm. ©2021 IEEE

comparison version had to be created that could be played on a conventional screen. Hence, using foam weapons should make the gameplay more interesting. Further, the players' visualized punching power increases the more opponents they defeat in succession. This mechanic is based on the idea of the motivational potential of the VPA mechanism, which was presented in the paper [BRM21] from Chapter 6. All enemies attack the players exclusively from the front, so they only have to move minimally to the sides but do not have to rotate around their own axis. Two versions of the game were created. The VR version of the game used an HTC Vive Pro, while the TV version used a 50-inch full HD TV. The foam weapons and thus the HTC Vive trackers were also used in the TV version. Only the output device was varied between the versions.

A quantitative evaluation was conducted after the development of the game. Arousal was recorded using the Self-Assessment Manikin. Cognitive performance was recorded using the Stroop Test. In the Stroop Test, 40 color words were presented to the subjects. The words were presented in a particular color and either congruent or incongruent with the printed word. The subject's task was to name the color in which the word was printed. The time it took the participants to name all the words and their errors were taken as indicators of cognitive performance. In addition, physical exertion (HR), perceived exertion (BORG), presence (IPQ), and enjoyment (IMI) were recorded. The study was conducted in a between-subjects design. Twenty female and twelve male subjects participated in the study. Physical exertion did not differ significantly between groups. However, no significant difference was observed between the groups regarding arousal and cognitive performance. Thus, contrary to what was assumed, the use of VR did not significantly increase arousal and cognitive performance. However, significantly higher values were observed in the VR condition than in the TV condition concerning enjoyment and presence. A positive correlation between presence and enjoyment was also observed. Interestingly, although no significant difference in physical exertion was observed, perceived exertion was significantly lower in the VR condition. In this context, negative correlations were also observed between the player's experience of presence and perceived exertion and between the player's enjoyment and perceived exertion. Although the results thus show no advantage of VR technology for arousal and cognitive performance in the context of exergames, they do consolidate the advantage of VR for presence, enjoyment, and even for perceived exertion in exergames.

Chapter 8

Discussion

In the previous five chapters, the five publications that form the core of this dissertation have been embedded into the overarching topic of this dissertation and presented in a summarized form. This chapter discusses the findings of these papers. However, the individual discussions of the respective papers' results in the context of the literature are part of the publications and, therefore, excluded from this chapter. Instead, this chapter presents a brief summary of the main findings concerning the five research questions that were presented in Section 1.1 at first. Subsequently, comprehensive contributions are presented and discussed, considering the findings of all papers. Afterward, limitations of these contributions and resulting directions for future research are identified. Finally, a conclusion complements this chapter and synopsis.

8.1 Summary of the Main Findings

RQ 1: Can VR enhance the player experience of exergames? Which impact do the output device, the perspective, and the tracking fidelity have? (Chapter 3)

Summarizing the results of the work [BAM19] it can be concluded that the output device, in particular, had the most significant impact on the PX for players in an exergame. Enjoyment, presence, embodiment, and performance were significantly higher in both VR versions than in both non-VR versions. The increase in enjoyment was independent of perceived exertion, which did not differ between groups and was similar to the physical exertion. Since the VR versions significantly increased the focus on internal body stimuli, VR did not distract from the strenuous exercise but significantly increased the players' focus on it instead. The first-person perspective had a significant advantage over the third-person perspective for embodiment and the experience of presence, but not for enjoyment. The difference in the body tracking technology did not result in a measurable, significant change for any of the constructs surveyed.

RQ 2: How can the exertion in a VR exergame be increased without reducing the motivation? (Chapter 4)

The results of the work [BMH20] show that using a heavy passive haptic controller significantly increased physical exertion compared to a conventional HTC Vive controller. The increase in physical exertion resulted in an increase in perceived exertion as well as an increase in associative focus. In addition, using the heavy passive haptic controller increased players' perceived pressure/tension, which is a negative predictor of enjoyment. However, enjoyment was not significantly reduced despite the increased exertion. The kinesthetic feedback generated by hitting the floor with the passive haptic controller increased parts of the presence experience and the proportion of subjects achieving a moderate or vigorous exertion level from 30% to 60%.

RQ 3: What impact does physical co-presence in a multiplayer room-scale VR game have on the player experience? (Chapter 5)

The findings observed by the work [BSM19] suggest that playing a two-player room-scale VR game in separate rooms, as opposed to playing in the same room, leads to significantly increased social presence, quality of communication, and performance. However, no differences could be observed between the two conditions regarding communication quantity and spatial presence. Furthermore, no differences between the conditions were observed regarding perceived freedom of movement and attentional focus on potential collision.

RQ 4: Can players of a VR exergame be motivated to engage voluntarily in an optional strenuous activity? (Chapter 6)

Summarizing the results of the work [BRM21] suggests that in a VR exergame, a virtual performance augmentation (VPA) mechanic is a solid motivator to perform an optional strenuous activity voluntarily. It was observed that the VPA mechanism was able to significantly increase the time spent performing an optional strenuous activity in contrast to a points mechanic as an incentive and to no additional incentive as a reward for performing the optional strenuous activity. Despite the higher exertion in the VPA condition, no significant difference in perceived exertion was observed between conditions. Furthermore, high values but no significant differences between conditions were observed regarding presence and enjoyment. The analysis of the individual motivation to voluntarily perform the additional strenuous activity supports the observed motivational potential of the VPA mechanism. In addition, the results suggest that the controller designed to perform the additional voluntary strenuous activity had an implicit motivational character in the gameplay context of the VR exergame.

RQ 5: What impact does VR have on cognitive performance and player experience in the context of an exergame? (Chapter 7)

The results of the work [BGM21] suggest that a VR system did not increase the arousal or the cognitive performance in an exergame compared to a conventional TV system. However, the analysis of the PX showed that the use of the VR system significantly increased the players' presence experience and enjoyment. A positive correlation between presence and enjoyment was observed as well. In addition, the use of a VR system significantly reduced the perceived exertion, while the difference in physical exertion was not significant between the conditions. Further, the players' experienced presence and enjoyment were negatively related to their perceived exertion.

8.2 Contribution

Based on the results of all papers, contributions for the understanding, future design, and research of VR exergames can be identified. These are presented and discussed in the following.

8.2.1 VR Significantly Enhances the Player Experience in Exergames

The comparison between a VR and non-VR exergame using a TV as an output device was analyzed in two studies in the context of this dissertation [BAM19; BGM21]. In both studies, it was observed that using the VR system significantly increased the perceived presence. The results thus confirm one of the basic assumptions of this thesis, that presence is a direct consequence of the degree of immersion [SW97; SU94]. Thus, it can be concluded that immersive VR HMD systems are a promising approach to increase the experience of presence in exergames. The experience of presence has been identified by Ryan and colleagues [RRP06] as an influencing factor for the emergence of intrinsic motivation or enjoyment in the context of digital games. This connection was also observed in our work. In both studies [BAM19; BGM21], an increase in enjoyment could be observed through the use of the VR system. In these studies, a significantly increased enjoyment was accompanied by a significantly increased experience of presence. Furthermore, in the studies [BMH20; BGM21] presented in Chapters 4 and 7, positive correlations between the presence experience and the players' enjoyment could be observed. Thus, these results support the findings of Ryan and colleagues [RRP06] that presence is an influential factor for players' enjoyment in digital games. Furthermore, this finding also confirms the core idea of this dissertation to incorporate VR as a technology in exergames to increase player enjoyment in contrast to conventional non-VR exergames. Also, the results of existing work [Sha+15b; McD+20] that systematically investigated the influence of VR in the context of exergames are confirmed by the findings of this dissertation regarding enjoyment. It is noticeable that the increase in enjoyment is independent of the purpose of VR. In the works of Shaw and colleagues [Sha+15b], and McDonough and colleagues [McD+20] an exercycle, and thus a repetitive movement was used as an exerting interaction. VR in these works was intended to distract the players' focus from the strenuous interaction to a virtual environment. In contrast to this, in our work, the strenuous interaction was generated by constantly changing demands within the virtual world. The exertion was deliberately focused. Nonetheless, a significant increase in enjoyment was shown by the use of VR technology in our work. Hence, regarding the enjoyment, it can be stated that VR can offer a significant benefit in the context of exergames independent of its purpose.

Concerning the lack of motivation as one of the main reasons for physical inactivity, it can be assumed that VR exergames are an encouraging way to address this problem. The enjoyment a person feels when performing a physical activity is crucial for recurrent and long-term engagement in that activity. Since our results suggest that VR can increase the enjoyment of conventional exergames, VR exergames are a promising tool to promote physical activity. For the recommended level of physical activity, it is irrelevant how many individual physical activity units it is composed of. Thus, even short play sessions, such as those found in the work presented in this dissertation, are beneficial for tackling the problem of physical inactivity. However, the motivational nature of VR is also a propitious finding beyond its integration into exergames. Unlike conventional gaming, VR games typically integrate body movements into the gameplay. Moreover, most current VR games are played while standing, breaking the sedentary paradigm of digital games. If the time that is otherwise spent sitting in front of a computer is spent standing by using a VR system, it would add significant benefit to approach the problem of sedentary behaviors. The high level of enjoyment that characterizes VR is a promising feature that can positively moderate the shift from playing while sitting in front of a screen to standing and walking around.

In addition to the experience of presence and the enjoyment, the results of the study [BAM19] presented in Chapter 3 also show that VR can offer a significant improvement for the sense of embodiment. Since embodiment is an influencing factor for the presence experience and thus also for enjoyment [KGS12; KPB14], this finding further confirms the advantage of VR over non-VR systems for exergames. However, it is noticeable that even without a body representation, VR was able to generate high presence and enjoyment values [BMH20; BRM21; BGM21]. Thus, based on our results, we can conclude that a complex body representation is not essential in the context of exergames for the experience of presence and enjoyment.

Beyond the direct comparison between VR and non-VR exergames, the results of all works on VR exergames [BAM19; BMH20; BRM21; BGM21] covered in this dissertation reveal that current HMD VR technology in the context of exergames can contribute to a very high enjoyment despite the potential limitations that this technology currently still has. The disadvantages that can arise from using VR systems, such as simulator sickness, sweat collecting under the display, or the weight and heat of the HMD, do not seem to harm the enjoyment. The comparison of the VR and non-VR technology in the context of exergames [BAM19; BAM19] show that the immersive advantage of the HMD is stronger than its potential disadvantages.

Thus, it can be summarized that in the context of exergames, VR provides a significant benefit for the player's enjoyment. The experience of presence, which results from the high degree of immersion of the VR system, is decisive for increasing enjoyment compared to non-VR systems. The enjoyment can be increased by VR, irrespective of the setup distracting from or focusing on physical activity. Regarding the crucial role of enjoyment or intrinsic motivation as an influencing factor for the regular performance of a physical activity, VR, in combination with exergames, can contribute significantly to a solution for the problem of physical inactivity. Future research and development on exergames that address the problem of physical inactivity should thus consider VR despite the potential drawbacks currently associated with the technology. In addition, the motivational potential of VR technology highlights the possibility that standing and physical movement could become central components of digital gaming if VR systems become established at home like current gaming consoles. Thus, VR could also contribute to the solution of the problem of sedentary behaviors.

8.2.2 VR Does not Have to Be Used to Distract from Exertion

Most works on VR exergames use a strenuous repetitive activity such as rowing or cycling as interaction with the game [ML20; Bar+18; Kou+20; Hal+19; Ija+20; Gre+20; KNVA19; Koj+19]. In most cases, VR is used as a technology to distract from the strenuous activity. The player's focus is directed to a virtual world to achieve a dissociative effect. This approach leads to increased enjoyment and reduced perceived exertion of VR- over non-VR systems [Sha+15b; McD+20]. The degree of immersion a technology provides enhances this dissociative effect [MEM11]. In contrast, the results of the work [BAM19] presented in Chapter 3 reveal a different picture. It was observed that VR could increase the players' enjoyment but not reduce the perceived exertion. Moreover, it was shown that VR enhanced the associative effect, contrary to the findings of Mestre and colleagues [MEM11]. The focus on body perception and thus exertion increased by using VR. Similar to the work of Finkelstein and colleagues [Fin+11], these results thus show that distraction from exertion is not required to be the goal of VR exergames. Especially concerning the problem of lacking motivation as a main reason for physical inactivity, this finding is interesting, as VR exergames can help to combine perceived exertion with enjoyment. Thus, an understanding could be created for the player that exertion can be enjoyable. The positive association of physical exertion could then provide a connotation for the real world beyond the context of exergames. Thus, this connotation may contribute to a change in the perception of the relationship between exertion and enjoyment.

One reason for the difference in the distracting or focusing character that VR has in the context of exergames can be seen in the nature of the game and the constantly changing challenges. In the works of Shaw and colleagues [Sha+15a] and McDonough and colleagues [McD+20], who observed a distracting character of VR in the context of exergames, repetitive exertion-based interaction was used that did not require conscious attentional focus and could be performed in an automatized fashion. In contrast, the work presented in Chapter 3 involved a constantly changing challenge that required the player to perform new and unpredictable body movements constantly. Thus, the strenuous interaction resulted not from a specific device such as an exercycle but the gameplay of the VR exergame. The results presented in Chapter 4 also support this assumption. In this work, an increase in exertion in VR was appropriately perceived as an increase and was nevertheless accompanied by high enjoyment scores. The increased exertion even led to an enhancement of the associative effect. Also, in this game, the exertion interaction was not predictable and resulted from the gameplay. In the work presented in Chapter 6, it was observed that despite a more significant amount of time pressing the controller together, the additional exertion was not reflected in the perceived exertion. However, unlike the other works of this dissertation, this strenuous interaction can be automated without conscious focus and is independent of the actual gameplay. These results thus support the view of the distracting or focusing nature of VR in exergames as a function of the nature of the exertive interaction and its integration into the game. In contrast, the results of the paper presented in Chapter 7 seem at first glance like a contradiction of this assumption. In this work, it was observed that the use of a VR system reduced the perceived exertion in contrast to a non-VR system and, at the same time, increased the enjoyment. The underlying game of this work was developed so that the necessary strenuous interaction does not rely on an additional device like an exercycle. However, in contrast to the works from Chapter 3 and 4, a much more predictable interaction was chosen in this work. All interactions were executed by continuously performing the same movements with the sword and shield. There was no need to move through space as in the work from Chapter 4, and no need to perform complex body movements as in the work from Chapter 3. The necessary interactions thus resembled more of a repetitive and automatable strenuous interaction like those in the works from Shaw and colleagues [Sha+15a] and McDonough and colleagues [McD+20] and thus could explain the reduced perceived exertion through the use of the VR system.

In summary, the results regarding perceived exertion in the context of enjoyment thus indicate that VR does not need to be used to distract from a strenuous interaction in exergames. Thus, for the conscious focus of exertion in the context of high enjoyment, VR games with constantly changing strenuous interactions are suitable. On the other hand, for deliberate distraction from exertion, a strenuous interaction should be chosen that can be automated and does not require a constant attentional focus. Especially with regard to the integration of VR exergaming into everyday life, the results reveal that complex setups integrating additional devices such as a rowing machine or exercycle are not necessary. Even currently commercially available devices like the HTC Vive can enable VR exergaming, combining enjoyment with exertion.

8.2.3 Increasing the Exertion Requires Appropriate Mechanics

Despite the beneficial effects that VR offers for enjoyment in the context of exergames, however, the question of whether VR exergames can also contribute to the WHO's recommended amount of physical activity is paramount concerning the fundamental problem of physical inactivity. The WHO recommends 150 – 300 minutes of physical activity in moderate intensity or 75 – 150 minutes in vigorous intensity per week for adults [Org10; Bul+20]. The results from the work [BAM19] presented in Chapter 3 suggest that the average intensity level for the Fit The Shape game corresponds to a moderate level of exertion and thus can contribute to the recommended amount of physical activity. However, increasing the activity level would reduce the amount of playtime required, thus promoting the exergame's efficiency.

To increase the exertion in VR exergames, two approaches were presented in Chapters 4 and 6, which differ fundamentally in their concepts. However, both approaches share the consideration that an increase in exertion can be accompanied by a reduction in enjoyment. In the work presented in Chapter 4, this relationship can be observed in the results. The conditions that led to increased physical exertion simultaneously caused increased pressure/tension, which is a negative predictor of enjoyment. Also, in the work presented in Chapter 6, a negative relationship between an exerting interaction and the motivation to perform it is evident. The strenuous voluntary interaction was performed significantly longer when a suitable motivator was present. Without this motivator, the strenuous exertion represented a somewhat aversive stimulus. Also, in the work presented in Chapter 7 the negative relationship between exertion and enjoyment is shown since a negative correlation between enjoyment and perceived exertion could be observed. Thus, it can be concluded that when a strenuous interaction is required to control and progress in a VR exergame, i.e., cycling to navigate through the game world, higher exertion can reduce enjoyment and hence needs to be integrated carefully. If, on the other hand, the exerting interaction is voluntary, i.e., pressing the controller longer to unlock an in-game booster, a suitable motivator is needed to perform it. Although the embedding of exerting interactions differs between the two papers, the results of them show that appropriate mechanisms need to be implemented to make an increase in exertion motivating.

In the work presented in Chapter 4, passive haptics was presented as a way to increase exertion for a VR exergame not distracting from exertion. The results show that player enjoyment was not reduced despite significantly increased physical and perceived exertion. Thus, increasing presence while increasing exertion seems to be a promising approach to design future VR exergames more exertive without reducing the motivational benefit of exergames. In the work presented in Chapter 6, VPA was elaborated as a motivating mechanic that can incentivize players to perform an optional exerting interaction voluntarily. The VPA mechanic could incentivize players to press the grip strength trainers together significantly longer than a points mechanic, and no mechanic could. However, the exerting interaction in that work can be classified as one that can be automated without conscious attentional focus. Thus, the increase in exertion in the VPA condition is not reflected in the perceived exertion. Moreover, an interaction based on strength rather than endurance was chosen. Whether the mechanism can thus be used to increase activity levels in VR exergames that consciously focus exertion needs to be clarified in future studies. Nonetheless, the results demonstrate the possibilities of the VPA mechanic and voluntary execution of optional strenuous activities to increase exertion in VR exergames.

In summary, it can be stated that the increase of exertion in exergames can be accompanied by a potential reduction of enjoyment and should therefore be integrated by suitable mechanisms. VR exergames in which the execution of an exerting interaction is not voluntary can increase exertion by integrating passive haptics and thereby prevent a potential reduction of enjoyment. If voluntary exertion execution is a central component of the VR exergame, appropriate motivating mechanisms such as VPA are needed to engage in voluntary exertion. In light of the central problem of physical inactivity and the fact that exergames are often motivating but do not contribute to the recommended amount of physical activity [Gra+07], the findings of the two papers can be used to support the design of future VR exergames that aim to combine high levels of enjoyment with high levels of physical activity.

8.2.4 Play Together but Spatially Separated

The results of the work presented in Chapter 5 are relevant for the design of future room-scale VR applications and thus also VR exergames. The results of the work show that playing in two separate rooms, as opposed to playing in the same room, has a positive effect on several constructs. Thus, a significantly higher social presence, a better performance, and a better-rated quality of communication could be observed when the players played in separate rooms. These findings are particularly relevant in the context of VR exergames played in a social setting. Multiplayer exergames can have significant advantages over singleplayer exergames in terms of enjoyment, exercise participation, and future play intention [SAC12; Paw+08; PC13]. In this context, social presence is a crucial variable that can positively moderate enjoyment [KT16] and also general exercise intention [WLT15]. In non-VR digital games, social presence is shown to be significantly enhanced when two players switch from a remote setting to a co-located setting [GDKI08a]. In contrast, the results from Chapter 6 show that a shift in this relationship occurs in a room-scale VR setting. Thus, the physical presence of the co-player has a constraining character in a room-scale VR setting. Even though the game developed for the work presented in Chapter 6 is a room-scale VR game that integrates movements in space and thus has an inherent physical activity component, no exergame constructs such as enjoyment or exertion were captured. However, based on the positive influence of social presence on these constructs, it can be assumed that remote settings can offer a significant advantage over co-located settings for multiplayer room-scale VR exergames. Based on the results of Gómez and Verbeek [GV16], who observed no significant difference in social presence concerning the physical presence of the co-player for a seated cardboard VR game, it can furthermore be assumed that the characteristics of the room-scale technology and the resulting interactions have a strong influence on the choice of setting. Thus, for exergames that do not require room-scale technology, as in the work of Shaw and colleagues [Sha+15b], and McDonough and colleagues [McD+20], it may not be relevant whether the game is played in two separate rooms or co-located.

For the design of future room-scale VR exergames, the results suggest that it is advisable not to have the players play in the same room or share the same play space. For increasing social presence, and thus potentially motivation and exertion, separating the physical presence of the players is beneficial. The interactions that come along with the use of room-scale VR technology seem to be crucial for the benefits of remote gaming.

8.2.5 The Extra Effort of Using VR for Exergames Is not Always Advantageous.

In addition to the presented and discussed benefits that VR offers in the context of exergames, some of the work also highlights limitations. The results of the work from Chapter 7 show that, contrary to our hypothesis, the use of VR as opposed to a TV as an output device does not influence arousal or cognitive performance. Both constructs are positively influenced by physical activity [Cha+12] as well as exergames [AH+12; GM12]. The VR system's higher degree of immersion does not seem to offer any further advantage in this regard. Although recent studies suggest that for long-term use VR may be beneficial for improving cognitive performance [Hua20], for short-term improvement VR does not seem to offer any added value. The limitation of the impact of a higher degree of immersion is also evident in the work from Chapter 3. While the work showed that using an HMD over a TV added significant value to presence, enjoyment, and performance, the difference between the tracking technology did not have a measurable impact. The higher resolution of the HTC Vive trackers provides a higher level of immersion compared to the Microsoft Kinect. However, the increase in the degree of immersion did not have a noticeable effect on the experience of presence or any of the other assessed constructs. Also, the results of the work from Chapter 5 suggest a limitation of VR technology. Sharing the same physical play space can reduce social presence compared to playing in separate rooms. The advantage co-located play offers to non-VR digital games [GDKI08a] is reversed by room-scale VR technology. Whether the social presence in separate rooms using room-scale VR is similar to that of co-located play in non-VR games, or whether the advantages of co-located play in terms of social presence can no longer be achieved through the use of multiplayer room-scale VR remains an open question. Nonetheless, multiplayer room-scale VR games thus require a complex setup or game concepts specifically tailored to the shared play space to increase social presence.

In summary, it can be said that the use of VR systems for exergames is depended on the desired impact. If exergames are used to increase arousal and improve cognitive performance, VR does not represent a benefit. Moreover, a higher level of immersion, such as that provided by the HTC Vive tracker, does not always affect player presence and enjoyment. In terms of social presence, the use of VR suggests that multiplayer gaming should take place in two separate spaces. Thus, for the design of future exergames, the exergame's purpose should be considered. While VR does not pose any significant disadvantage in the context of exergames, the increased effort for the development and setup of a VR exergame is not always necessary.

8.3 Limitations and Possible Future Work

Like all scientific work, the presented research and findings are subject to certain limitations that should be considered when interpreting the results of this thesis. A distinction can be made between limitations that refer to the respective papers or that can be considered in the context of the entire dissertation across all publications. The limitations of the individual publications are presented in the respective papers and will not be discussed here. Instead, the broader limitations are presented in this section. In all studies, evaluations were conducted with a primary student sample. Thus, the samples do not represent the general public regarding age, ethnicity, social status, and culture. Thus, generalization should not be undertaken without further research with more diverse samples. In addition, the sample sizes of the papers from Chapter 6 and 7 are smaller compared to the other papers. This derives from the COVID-19 pandemic and the difficult conditions of conducting studies. The test power of the results of these studies may therefore be reduced and interpreted with care.

Physical exertion was classified in the papers via heart rate. However, the heart rate is regulated not only by physical exertion but by various processes of the autonomic nervous system [McC07]. Therefore, the heart rate can be affected by several factors besides physical exertion. Since additional parameters like maximal oxygen uptake were not considered due to the complexity of the resulting setup, a limitation in the statement about the intensity level can be seen.

Furthermore, all studies did not focus on physically inactive individuals. The proportion of individuals with low physical activity levels was low across the papers. A person's physical activity status was not a determining factor for participation in the studies. Particularly concerning the use of VR exergames to increase physical activity in physically inactive individuals, the results of this work are thus limited in terms of transferability. However, the results of the paper in Chapter 4 show that the results of the work do not change when regular physical activity is taken into account. Based on the findings of Shaw and colleagues [Sha+15b], who observed a negative correlation between regular physical activity and the enjoyment of playing a VR exergame, it can be assumed that our findings are also transferable to primarily physically inactive samples, but future studies should clarify this. Another limitation is that no long-term effects were examined in the research presented. Thus, the results in all studies refer to the one-time playing of a game or a game version. Whether the results can be transferred to the long-term use of the respective game cannot be derived. However, the enjoyment that is felt during the execution of an activity is decisive for the long-term and frequent use of this activity. Even though the work in this dissertation only examined enjoyment and related variables in one-time play sessions, the results represent the potential of the technology. They thus can be used as a positively evaluated basis for examining VR exergames for long-term use. In this context, another limitation is the potential occurrence of the novelty effect. The effect describes increased interest in an activity not because of the activity but because of interest in the technology used [Cla83]. Primarily since no long-term studies were conducted in the papers, novelty effects may have occurred due to the low prior VR experience of the subjects. A further limitation may be seen in the fact that, except for the work presented in Chapter 6, the physical challenge of the game was not adapted to the players' abilities. While the exertion required was tested and adjusted regularly during the development of the games, it was not individualized for any of the study participants. Concerning the experience of competence, which is an influencing factor for intrinsic motivation and is affected by a fit of ability and challenge [RD00a], the neglect of the consideration of individual difficulty levels may have had a potentially negative impact on enjoyment. However, since very high enjoyment scores were consistently found in all work on VR exergames of this dissertation, the chosen difficulty level of the respective games seems appropriate for most participants. In addition, the physical challenge of all presented games is relatively low compared to athletic workouts in the high-intensity range. Whether the results of this work are transferable to VR exergames that aim for a consistently high-intensity level or even want to address athletes should be clarified in future studies.

Furthermore, another limitation is the application of our results for the public in the context of current VR technology. In contrast to smartphones, PCs, or gaming consoles, VR systems are currently not well established and are rarely found in private contexts. In addition, VR systems for use in the home require an accessible play space, which is considerably larger than that used by conventional gaming systems, especially for exergames. In addition, current HMDs are comparatively heavy and can cause simulator sickness, especially during prolonged use [Mos+11]. VR exergaming is thus currently still associated with many limitations, which could, however, improve significantly in the coming years due to the constant improvements in VR systems and the establishment of the technology. Even if the results of this work cannot be directly used to address the problem of physical inactivity and sedentary behavior, they serve as an insightful research basis and guidelines for future research and development.

Based on these limitations, directions for future research can be identified. First, future work should investigate the long-term potential of VR exergames in terms of their motivational appeal. For this purpose, research designs such as that of Rhodes and colleagues [RWB09], and Warburton and colleagues [War+07] would be conceivable. One or more pre-installed VR systems could be made available in rooms at the university. Participants would then be able to play with this system as often as they wish during the study period. In addition to investigating long-term motivational potential, this design would also support the voluntary nature of subjects' participation and could thus provide a comprehensive picture of the system's motivational potential. The influence of the novelty effect could also be investigated in the process. Another possibility would be to provide subjects with a system for private use. Hence, it could be investigated how VR exergames would be voluntarily integrated into the participants' daily lives. Furthermore, future studies that consider VR exergames in the context of physical inactivity should consider physically inactive samples. In this context, the respective individual reasons for physical inactivity should also be recorded in order to be able to allow a detailed statement about the motivational potential of VR exergames in individuals who have a low motivation for regular physical activity. To classify the physical exertion more precisely, additional constructs such as the maximal oxygen uptake should be recorded in addition to the HR. In order to adapt the challenge of VR exergames to the players' abilities, future developments should also enable individual difficulty levels. Conceivable here would be either a classic form of difficulty adaptation before the game is started or a live adaptation during gameplay. A continuous adaptation of the difficulty based on the %HR or %HRR could lead to the required exertion being achieved more efficiently and maintained throughout the game while taking better account of the players' individual physique. The dissertation focused on the idea of improving the player's enjoyment in exergames through the high level of presence experience induced through the high immersion level of VR. Immersion was understood as a technical property of a system. However, based on the SCI model of Ermi and Mäyrä [EM05], immersion in games can also be enhanced by optimal challenge and imaginative aspects. Moreover, the presence experience represents only one influencing factor for the enjoyment of digital games. Autonomy, competence, and relatedness are other factors that can increase enjoyment. Future work that aims to develop highly motivating exergames can thus consider other aspects besides increasing presence through sensory immersion.

8.4 Conclusion

In summary, this dissertation contributes to the understanding, research, and future design of VR exergames. The work presented in this dissertation shows that using VR in exergames significantly enhances the players' motivation compared to using conventional non-VR systems. The experience of presence, which results from the high immersion level of the VR system, is crucial for this advantage. This dissertation thus confirms, on the one hand, the connection between immersion and presence and, on the other hand, between presence and motivation in digital games. Furthermore, this dissertation contributes to an understanding of the effect VR has in exergames depending on the type of the exerting interaction. VR can be used to distract from exertion during monotonous activities. However, VR can also strengthen the focus on exertion when interactions result from constantly changing gameplay. Regardless of the purpose of use, the results of this dissertation show that VR can enhance players' enjoyment. Consciously focusing on the exertion that results from physical activity can thus be combined with high enjoyment, providing a good base to connote physical exertion for physically inactive individuals positively. The work in this dissertation that has focused on the deliberate increase of exertion further demonstrates that appropriate mechanics are needed to increase exertion to compensate for the accompanying reduction in enjoyment. Two approaches have been presented in this regard: The first approach focused on the simultaneous increase of exertion and enjoyment by integrating a heavy passive haptics controller. The second approach focused on the performance of a strenuous voluntary activity, which was incentivized with a motivating game mechanic. Both works contribute to understanding the relationship between exertion and enjoyment in the context of VR exergames. In addition, the works demonstrate two approaches to increase exertion in a motivating way. For the understanding of multiplayer room-scale VR, it was found that sharing the same play space has a negative impact on the social presence, and future work should thus focus on playing in two separated spaces. In addition to the advantages and influences of VR in the context of exergames, it was also found that VR does not offer any added value for exergames in terms of cognitive performance and arousal. This finding contributes to the understanding of which aspects the additional effort of VR development in the context of exergames provides an advantage for and which it is not affecting. Across all the work, it was found that despite the current limitations that VR technology still has, it can already generate significant benefits over the currently established TV screen technology. Future work should particularly investigate the long-term effects of VR in the context of exergames, taking a physically inactive sample into account, to work out whether the findings of this dissertation can be used to establish a long-term motivation for regular physical activity.

The results, as well as the developed games and mechanics of this dissertation, thus serve research and development of future VR exergames alike and can help researchers, designers, and developers understand and utilize the motivational potential of VR in exergames. This dissertation enables future VR exergames to become more motivating and effective, thus motivating more people to be more physically active.

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Declaration

I hereby declare that this thesis was complied solely by myself and only with the references marked and cited.

Duisburg, June 14, 2022

Felix K. Born

Colophon

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Chapter 9

Attached Publications

In the following, the five publications on which this dissertation is based are attached. The order of the publications is shown below on the page. The respective papers are published in US Letter paper size (215.9mm $\times$ 279.4mm). Since this thesis was written and printed in A4 paper size (210mm $\times$ 297mm), the publications were automatically adjusted to the A4 paper size.

1. **Born, F.**, Abramowski, S., & Masuch, M. (2019, September). Exergaming in VR: The Impact of Immersive Embodiment on Motivation, Performance, and Perceived Exertion. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)* (pp. 1–8). IEEE. DOI: 10.1109/VS-Games.2019.8864579

2. **Born, F.**, Masuch, M., & Hahn, A. (2020, August). Ghost Sweeper: Using a Heavy Passive Haptic Controller to Enhance a Room-Scale VR Exergame. (Best Paper Nomination) In *2020 IEEE Conference on Games (CoG)* (pp. 221–228). IEEE. DOI: 10.1109/CoG47356.2020.9231867

3. **Born, F.**, Sykownik, P., & Masuch, M. (2019, August). Co-Located vs. Remote Gameplay: The Role of Physical Co-Presence in Multiplayer Room-Scale VR. In *2019 IEEE Conference on Games (CoG)* (pp. 1–8). IEEE. DOI: 10.1109/CIG.2019.8848001

4. **Born, F.**, Rygula, A., & Masuch, M. (2021, September). Motivating Players to Perform an Optional Strenuous Activity in a Virtual Reality Exergame Using Virtual Performance Augmentation. In *Proceedings of the ACM on Human-Computer Interaction, 5.* CHI PLAY (2021). (pp. 1–21). DOI: 10.1145/3474652

5. **Born, F.**, Graf, L., & Masuch, M. (2021, August). Exergaming: The Impact of Virtual Reality on Cognitive Performance and Player Experience. (Best Paper Nomination) In *2021 IEEE Conference on Games (CoG)* (pp. 1–8). IEEE. DOI: 10.1109/CoG52621.2021.9619105

Publication

Title:

Exergaming in VR: The Impact of Immersive Embodiment on Motivation, Performance, and Perceived Exertion.

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The following version is the accepted version and not the final published version of the paper.

Exergaming in VR: The Impact of Immersive Embodiment on Motivation, Performance, and Perceived Exertion

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***Abstract*—Digital games which are controlled by physical movements - so-called exergames - have beneficial effects on the player's motivation to exercise. Since VR exergames can facilitate the potential impact on the player's motivation, we investigate the role of immersion and related constructs for a room-scale VR exergame. Thus, we developed four different versions of a digital exergame by manipulating the immersion (room-scale VR vs. common screen), perspective (first vs. third person) and tracking fidelity (HTC Vive Tracker vs. Microsoft Kinect). Our results of a study with 47 participants suggest that immersion and perspective in particular can significantly increase the player's presence, embodiment, motivation, and performance independent of the perceived exertion which was not affected by any condition. Our research gives novel insights which advantages modern room-scale VR systems can offer and how immersion influences the relationship between motivation, performance, and perceived exertion.**

***Index Terms*—virtual reality, exergaming, embodiment, motivation, perceived exertion, tracking fidelity**

I. Introduction

Digital games focusing on physical exercising are called exertion games or *Exergames*. The authors of [24] define exergames as digital games "*[...] where the outcome of the game is predominantly determined by physical effort*". With the introduction of Microsoft's Kinect, Sony's Eye Toy and Nintendo's Wii, exergaming became a widely popular and affordable part in the entertainment industry and thus led to a strong research focus. Prominent exergame examples such as Wii Sports - which is the best-selling console game of all time with more than 82 million units sold[1] - show a significantly higher energy expenditure than common sedentary games [13] and can offer social benefits to a greater extent [17]. Furthermore, exergames can have positive effects on the player's mood and emotional well-being [10] and can be used in a variety of applications to support physical rehabilitation as well as psychological therapy [1], [10], [22]. Since the U.S. Healthcare Gamification Market generated over US$ 16 billion in 2016 and expects to achieve an average annual growth rate of more than 12% from 2017 to 2024, exergames as the primary game type in this domain are likely to gain more popularity[2].

A variety of studies has demonstrated, that increasing the immersion in exergames can increase the player's feelings of energy [29], the training's intensity and motivation [8] and can lead to better performance [25] and reduced perceived exertion [23]. Since Virtual Reality (VR) systems featuring a head-mounted display (HMD) offer the highest level of immersion the impact of VR on exergaming is a promising approach [32], [39]. Hence, we refer to the term VR exergames as exergames including an HMD and thus providing a fully-immersive experience.

In our research, we investigated the positive effects of a highly immersive room-scale VR exergame compared to a non-VR setting. In contrast to existing immersive exergaming research [16], [32], [37], [39], we do not focus on using virtual environments as a distractor from the physical task and thus at reducing the perceived exertion for repetitive physical exercises like cycling or running on a spot. Instead, we use VR as a game element and hence create a more realistic application to increase the player's presence and thus the motivation for physical exercises that require a high amount of body perception. We examine the impact of the degree of immersion, the player's perspective, and the tracking fidelity on vital constructs like motivation, performance, presence, embodiment, engagement, and perceived exertion using subjective and physiological data.

Our results suggest that in particular immersion and perspective have a significant impact on the player's motivation and performance among other constructs - although, in contrast to existing research, the perceived exertion did not differ between our examined groups. However, our results indicate,

[1]Best selling console games worldwide 2019: http://www.vgchartz.com/gamedb/

[2]Healthcare Gamification Market size: https://www.gminsights.com/industry-analysis/healthcare-gamification-market

that a highly immersive VR environment can significantly increase the player's motivation and performance. Our work contributes to the design of exergames that aims at supporting more complex movements which can be found in physical rehabilitation. We mainly address designers of exergames who seek to take advantage of the motivating effects an immersive exergame can offer while using room-scale VR to focus on body awareness. Thus, for instance, the insights can be used to support patients in physical rehabilitation where a motivational lack of patients is a central problem [31].

II. The Impact of Immersion in Exergames

The work of [35] defines immersion as an objective characteristic of a technology, which describes *"[...] the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant"*. In the context of exergaming, immersion has the potential to influence the player's perception and behavior positively.

The authors of [15] examined the impact of immersion on the perceived exertion of exergame players. Their task was to ride a stationary bicycle, either in front of a PC-Desktop screen, a projection, while wearing an HMD, or without any screen in front of them. They observed a significantly lower perceived exertion in the HMD and projector condition compared to the no screen group although no differences were found between the HMD and projector group. These results are supported by [23] who discovered a significantly lower perceived exertion and higher fun experiences of subjects riding a stationary cycle in front of a semi-immersive projection of a virtual environment compared to no digital distractor and by [38] who evaluated VR exergames using the HTC Vive.

Further, [8] developed the immersive exergame *Astrojumper* which is played inside a three-sided stereoscopic cave environment. Their game does not consider virtual environments as a distractor from a physical task but instead allows the player to focus on her/his own body movements. The authors observed that high levels of motivation were accompanied by high levels of perceived exertion. Though the game *Astrojumper* was continuously developed and adapted by [7], [26], [27] the impact of the representation, perspective, or tracking hardware needs further evaluation.

A. Presence and Embodiment

A high level of immersion is a prerequisite for the user's experience of presence in a virtual world [34], which is often defined as presence or the feeling of "*being there*" [14]. Apart from the fundamental impact of design choices [28], [37] point out that the motivating effects in immersive exergames are directly related to the technical properties of the system, and that presence is positively correlating with motivation. The authors of [34] point out that a high experience of presence can be achieved using a high display resolution and quality of presentation as well as using a virtual (body) representation, whose appearance and movement match those of the corresponding user.

A related central construct in this context is the sense of embodiment which is described by [18] as *"[...] the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body"*. The authors of [20] have demonstrated, that higher degrees of embodiment positively affect the user's experience of presence, enjoyment, intention to further play the exergame, and level of energy expenditure. The work of [36] has shown that a high degree of immersion can positively influence body ownership and agency, which are two central aspects in the sense of embodiment [18]. Furthermore, [36] discovered that an individualized avatar, which is similar to the player, can positively increase body ownership and the experience of presence. Additionally, the authors argue that agency is influenced by the visual-motoric synchronicity based on the used body tracking system.

Furthermore, a central influencing factor for the sense of body ownership and thus embodiment is the perspective of the player inside a virtual environment. The work of [33] observed an impact of a first-person perspective in contrast to a third-person perspective on the experience of body ownership. Further, [6] discovered a significant increase in the experience of presence when a player perceived the virtual world in the first-person perspective, although the examined game was a common non-VR game. For VR games, perspective, as well as the mapping of the player's body movements to the virtual representation, can positively influence the sense of embodiment [9]. However, current research suggests that the experience of presence can occur equally, regardless of the perspective in VR environments [12], [19]. While using the first-person perspective for precise movements in VR can be advantageous [12], being able to evaluate one's own movement in the third-person perspective could also be beneficial [32].

B. Contribution

Although several immersive exergaming studies observed positive effects for the player's motivation, the relationship between immersion, perceived exertion and motivation is not apparent. Most of the immersive exergaming research is focusing on using virtual environments in VR and non-VR systems as a distractor from a monotonous physical task [15], [16], [23], [25], [37]. So far only little research has been published on immersive exergaming where a focus on complex physical movements is a central element and where VR cannot be used as a distractor [8], [7], [26], [27]. To this date and the authors' knowledge, there is no VR exergaming research which uses an HMD to create a fully-immersive experience and integrates the whole player's body and thus focuses on realistic body perception. Therefore, we created a room-scale VR exergame focusing on precise physical movement rather than distracting the player's attention. Furthermore, we track the player's movements and precisely map them onto a virtual representation. We investigate the impact of VR, tracking fidelity, and perspective on important constructs like motivation, presence, sense of embodiment, and exertion.

III. Fit The Shape

The exergame *Fit The Shape*, which was inspired by the Japanese game show “Hole in the Wall”, serves as the basis for the experimental study presented in this paper. *Fit The Shape* was developed using *Unity3D*. Since our study aims to examine the effects of the degree of immersion, tracking fidelity and perspective, four different versions were implemented, each offering individual manipulations of these factors.

Figure 1 presents the basic gameplay that is identical in each version. The player is represented either by a female or a male virtual character. In total, 40 walls, each consisting of 836 cubes, move towards the player. The cubes are arranged in such a way that they form different cut-outs in the wall. The main objective of the player is to form herself/himself into the shapes in the wall without colliding with the cubes. If any parts of the body hit cubes, they break apart. The maximum points for every wall amount 1000. For each cube the player hits, 10 points are subtracted. The number of cubes hit aims exactly at the key requirements of *Fit The Shape* which focus on precise movements, balance, and coordination. Being aware of one’s own body position is a vital prerequisite for the player’s success. Notably, each exercise is designed to require moving several parts of the body in the right position rather than including only single parts of the body which indicates the importance of body awareness and proprioception.

In a first step, we created a version of *Fit The Shape* that is played in front of a conventional screen using Microsoft Kinect for motion capturing. We then extended this version by a VR-version using the HTC Vive and Vive’s tracking technology for motion capturing. Therefore, six Vive Trackers were attached to the feet, wrists, and elbows of the player. In order to integrate the movements of the pelvis, an HTC Vive Controller was attached to a belt. Furthermore, the player’s head was tracked with the HMD. We used inverse kinematics to map the body movements correctly to the virtual character.

Moreover, as visuomotor synchrony can influence the sense of body ownership [9] a third version was implemented replacing the Microsoft Kinect (30 FPS) in the non-VR-version with Vive’s tracking technology (120 FPS). Consequently, the impact of the tracking device can be systematically investigated as the influence of different output devices is eliminated.

Since perspective can be regarded as an essential factor in the context of exergames, we created a fourth version of *Fit The Shape* that adapts the third-person perspective of the VR-version to the first-person perspective, as presented in figure 2. Since in this version the proportions of the virtual character have to match the proportions of the real human body, the character and world are adapted automatically prior to the start of the game. We deliberately neglected a first-person perspective for the non-VR-versions since a virtual character displayed on a conventional screen in the first-person perspective is not visible for the player.

TABLE I
Study versions of *Fit The Shape*

Version	Output Device	Tracking Device	Perspective
VR1PP	HTC Vive	Vive Tracker	First-Person
VR3PP	HTC Vive	Vive Tracker	Third-Person
Tracker	Common Screen	Vive Tracker	Third-Person
Kinect	Common Screen	Kinect	Third-Person

Overall, as summarized in table I, four versions were implemented representing variations of the output device, tracking device, and perspective.

IV. Evaluation

We conducted a comprehensive study to investigate the impact of the immersion, perspective, and tracking fidelity on several important constructs which influence the player’s behavior and engagement in exergames. Based on the literature research we hypothesize that an increase of immersion positively influences the player’s motivation, fun, performance, presence, engagement, and embodiment. Since the results of current VR exergaming research regarding the perceived exertion are not homogeneous, we further investigate the perceived and objective exertion in dependence on the degree of immersion and perspective.

A. Method

We used the Borg Scale [2] to examine the perceived exertion. The scale ranges from 6-20 (none - very, very hard). The actual exertion was operationalized using the heart rate which we measured using a POLAR H7 pulse belt every participant had to wear during the whole experiment. Following a similar approach to [38], we calculated average heart rates and values of perceived exertion as percentages of the maximum heart rate so that the values can be compared appropriately between participants. Using these values, differences between perceived exertion and physical exertion were determined and compared between the different versions.

The motivation was measured using the Intrinsic Motivation Inventory (IMI) [5].

The scale consists of six subscales, including *Interest/Enjoyment* which is considered the most significant subscale since it directly measures intrinsic motivation. The performance was measured using the total numbers of cubes, that were hit out of the wall for every contact point. The better the player fits into the shape, the fewer cubes are hit.

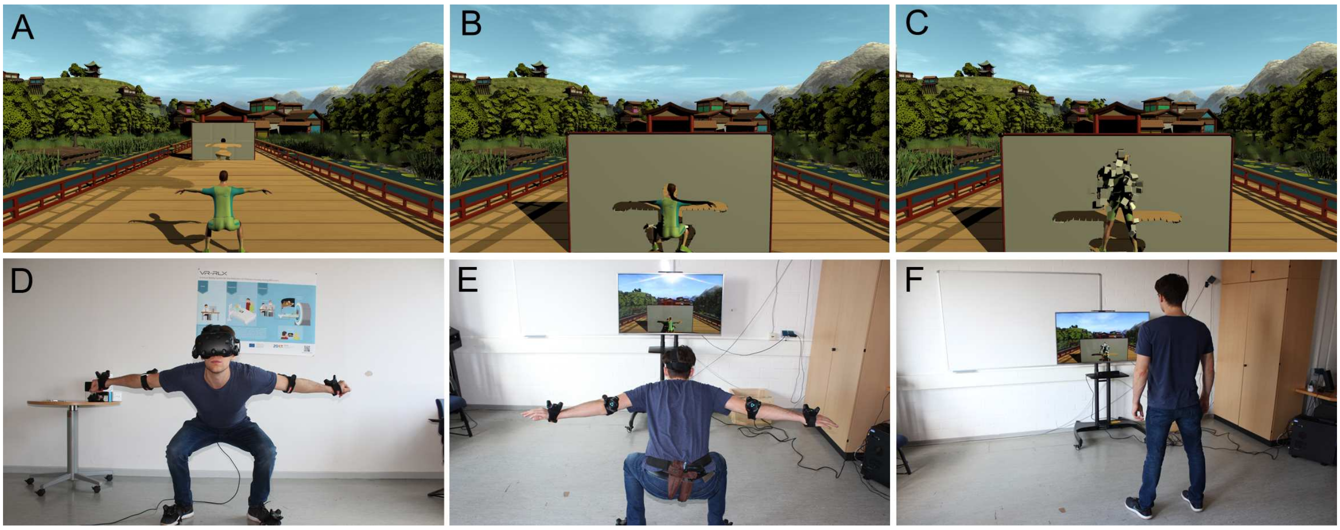

Fig. 1. **(A)** A wall is moving towards the player, who has to get into a squat pose in order to fit into the shape. **(B)** If she/he manages to fit into the shape perfectly, no cubes are pushed out. **(C)** For all contact points with the wall, cubes will fall out. **(D)** In the *VR1PP*- and *VR3PP*-variant six HTC Vive Trackers are attached to the player while wearing an HMD. **(E)** In the *Tracker*-variant, the player plays in front of a TV screen. The head movement is tracked using an HTC Vive Tracker attached to a head strap. **(F)** In the Kinect-version the player plays in front of a TV screen without any further tracking sensors.

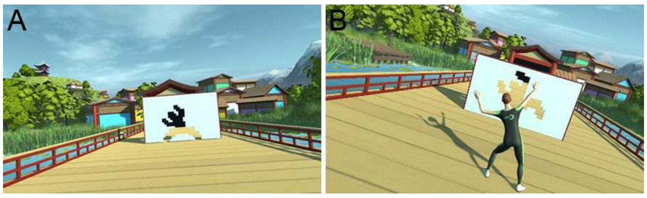

Fig. 2. **(A)** The player's perspective in the VR1PP-version of *Fit The Shape*. **(B)** The player's perspective in the VR3PP-version of *Fit The Shape*. The rotation of the camera in the game in both versions depends on the rotation of the player's head since the user wears an HMD in both versions.

The experience of presence was measured using the Igroup Presence Questionnaire (IPQ) [30]. The Game Engagement Questionnaire (GEQ) [3] was used to assess the engagement which serves as an indicator for the player's level of game involvement. Following the research from [9] we used six questions in total to measure the sense of embodiment - 2 questions for each component(*Agency, Body Ownership, and Self-Location*).

Since existing research focused on virtual environments as a distractor from a monotonous physical task and our application uses VR and body perception as game elements, we measured the participants' dissociation and association. Congruent with the research of [23] dissociation is defined by a focus on external stimuli and distance to internal body stimuli whereas association describes the focus on internal body stimuli. This attentional focus could be rated on a scale from 0 (dissociation) to 10 (association).

B. Design and Procedure

In our study, we used a within-subject design. Hence, every participant played each of the four versions of *Fit The Shape*. The same dependent variables have been assessed after each game was tested. To eliminate order effects, we assigned the participants in such a way that no possible order of the total 24 orders, was played more than two times. The requirements for performing repeated measures ANOVAs were tested and if the assumption of sphericity has been violated, the Greenhouse-Geisser adjustment was used. According to the Central Limit Theorem [21], we can assume that the distribution of the sample mean is normal since our sample size is greater than 30. Additionally, the ANOVA is considered to be robust against violations to the normality assumption [11]. Prior to the start of the procedure, the participants gave their consent and had to put on the pulse belt while the instructor waited outside the laboratory. Afterward, demographic data and previous experiences with digital games and VR were assessed. Furthermore, the International Physical Activity Questionnaire (IPAQ) [4] was used to assess the daily physical activities of the participants. During this period, we continuously measured the heart rate and calculated an average baseline heart rate which represents no physical activity, which we later compared to the heart rate values during the gameplay. Afterward, the participant played one round of the respective version, which consisted of 40 incoming walls and thus lasted 3 minutes regardless of the version. After each gaming session, the described questionnaires were filled out. With the end of the fourth version and the filling of the respective questionnaires, the participants were debriefed about the experiment. The complete experiment lasted 90 minutes in total.

C. Participants

47 participants aged 18 - 24 were recruited. Exclusion criteria were a history of neurological diseases such as epilepsy. Three participants were excluded from the study since techni-

cal problems did not allow to play the game in these particular cases. Therefore, 44 participants were included and considered in the statistical analysis. We calculated an a priori power analysis with G*Power to determine the required sample size for one-way ANOVAs with four repeated measurement points. To detect a medium effect with a power of .95 and an alpha of .05 having an assumed correlation between the measurement points of $r = .40$ the analysis revealed a sample size of 43. Since 44 participants were included in the analysis, this requirement is fulfilled. All participants gave written informed consent before the experiment and received 1.5 hourly credits as a trial subject, which have to be collected in several degree courses. The study was approved by the ethics committee of our university.

D. Results

32 female and 12 male students were included in the analysis ($N = 44$). The age ranges from 18 - 24 ($M = 21.42$, $SD = 1.41$). In average participants play digital games $M = 5.40$ ($SD = 7.18$) hours a week. The experience with exergames can be considered low with 29 participants reporting that they have never played an exergame. Furthermore, 18 participants reported no experience with VR. Using the IPAQ, the athletic activity of the participants was categorized. 4 participants were categorized as low, 17 as moderate, and 23 as high.

Presence

As shown in table II the values for all subscales highly differ between all groups. For the *General Presence* subscale, a repeated measures ANOVA revealed a significant difference $F(3, 129) = 60.67, p < .001, \eta_p^2 = .59$. Post hoc comparisons indicate a significant difference between the VR1PP- and VR3PP-version ($p = .008$) and between the VR1PP- and Tracker-version ($p < .001$) and between the VR1PP- and Kinect-version ($p < .001$). The differences between the VR3PP- and Tracker- and Kinect-version are significant as well with ($p < .001$). The Tracker- and Kinect-group nearly differ with ($p = .068$). Similar results were found for the *Spatial Presence* subscale in which only no significant difference was found between the Kinect- and Tracker-group. All other groups showed significant differences. For the *Involvement* and *Experienced Realism* subscale repeated measurement ANOVAs revealed significant differences between both VR-groups and non-VR-groups, but no significant differences between the VR-groups or between the non-VR-groups.

Embodiment

The embodiment values for all groups can be considered quite high. As shown in table II a dichotomy is identifiable due to the similar values of both VR-groups as one unit and similar values of both non-VR-groups as the other unit. A repeated measurement ANOVA revealed a significant difference between the groups for *Agency* $F(3, 129) = 16.93, p < .001, \eta_p^2 = .28$, for *Body Ownership* $F(3, 129) = 20.42, p < .001, \eta_p^2 = .32$, and for *Self-Location* $F(3, 129) = 23.70, p < .001, \eta_p^2 = .36$. For the *Agency* component pairwise comparisons revealed significant differences for both VR-versions compared to both non-VR-versions ($p < .001$). No significant differences were found between the VR-groups and between the non-VR-groups. The same dichotomy was found for *Body Ownership* though for this component also a significant difference between the VR1PP- and VR3PP-group was found ($p = .016$). The same pattern was found for the *Self-Location* component. Here a difference between the VR-versions was found with ($p = .044$). The remaining significant values are similar to the other components with no significant difference between the non-VR-versions.

Motivation

The overall results of the IMI show rather high average values in all subscales. Statistical analysis indicates a significant difference regarding the *Interest/Enjoyment* subscale that directly assesses intrinsic motivation, $F(3, 129) = 10.06, p < .001, \eta_p^2 = .19$. The mean score for the *Interest/Enjoyment* subscale is significantly higher ($p < .001$) in the VR1PP-version (*M* = 5.35, *SD* = 1.15) than in the Tracker-version (*M* = 4.71, *SD* = 1.38) and in the Kinect-version (*M* = 4.59, *SD* = 1.39). The VR3PP-version shows the same tendency, since the mean score (*M* = 5.23, *SD* = 1.29) significantly differs from the Tracker-version (*p* = .003) as well as from the Kinect-version (*p* = .001). No significant differences were found between the VR1PP-version and the VR3PP-version or between the Tracker-version and the Kinect-version.

Performance

Regarding the user's performance, results indicate a dichotomy: In both non-VR-versions participants hit a rather high number of cubes, whereas average numbers of cubes hit in the VR-versions were comparatively small. Accordingly, there is a significant effect of the versions of *Fit The Shape* on the performance: $F(3, 129) = 39.41, p < .001, \eta_p^2 = .48$. Post hoc comparisons show that participants hit significantly less cubes in the VR1PP-version (*M* = 1410.59, *SD* = 259.91) and in the VR3PP-version (*M* = 1479.64, *SD* = 201.44) than in the Tracker-version (*M* = 1710.66, *SD* = 191.89) and the Kinect-version (*M* = 1699.73, *SD* = 155.48), (all $p < .001$). Moreover, performance tended to be better in the VR1PP-version than in the VR3PP-version (*p* = .061). No significant differences were found between the non-VR-versions.

Exertion

Average Borg ratings equal 12.50 (*SD* = 2.22) in the VR1PP-version, 12.18 (*SD* = 1.81) in the VR3PP-version, 11.93 (*SD* = 2.26) in the Tracker-version and 11.82 (*SD* = 2.32) in the Kinect-version, which can be all classified between light and somewhat hard ratings of perceived exertion [2]. In table III the average values of perceived exertion, as well as the average heart rate, both as percentages of the maximum heart rate, are presented. The values indicate that in each version of *Fit The Shape* values of perceived exertion were above physical exertion. The differences between the two

TABLE II
IPQ AND EMBODIMENT SCORES

Subscales	VR1PP M *(SD)*	VR3PP M *(SD)*	Tracker M *(SD)*	Kinect M *(SD)*	*p*
IPQ					
General Presence	4.36 (*1.42*)	3.68 (*1.65*)	1.95 (*1.57*)	1.52 (*1.58*)	$< .001$
Spatial Presence	4.07 (*1.31*)	3.49 (*1.36*)	2.00 (*1.19*)	1.83 (*1.34*)	$< .001$
Involvement	3.02 (*1.58*)	2.93 (*1.64*)	1.45 (*1.04*)	1.47 (*1.13*)	$< .001$
Experienced Realism	2.08 (*0.89*)	1.87 (*1.09*)	1.37 (*0.96*)	1.14 (*0.83*)	$< .001$
Embodiment					
Agency	2.30 (*0.81*)	2.26 (*0.80*)	1.50 (*1.04*)	1.31 (*1.21*)	$< .001$
Body Ownership	0.41 (*1.67*)	−0.26 (*1.73*)	−1.26 (*1.63*)	−1.36 (*1.51*)	$< .001$
Self Location	1.14 (*1.60*)	0.56 (*1.70*)	−0.45 (*1.57*)	−0.88 (*1.54*)	$< .001$

TABLE III
AVERAGE VALUES OF PERCEIVED EXERTION AND PHYSICAL EXERTION AS A PERCENTAGE OF THE MAXIMUM HEART RATE

	Borg Values	Heart Rate
VR1PP	64.82%	58.16%
VR3PP	63.31%	59.62%
Tracker	61.31%	57.55%
Kinect	59.79%	56.98%

measures of exertion are equal to 6.66 (*SD* = 12.56) in the VR1PP-version, 3.69 (*SD* = 10.04) in the VR3PP-version, 3.77 (*SD* = 11.29) in the Tracker-version and 2.81 (*SD* = 11.15) in the Kinect-version. Results of a repeated measures ANOVA indicate no significant difference between the game versions regarding the differences between perceived exertion and physical exertion.

Dissociation & Association

The mean values of the VR1PP-version (*M* = 8.14, *SD* = 1.82), the VR3PP-version (*M* = 8.09, *SD* = 1.44), the Tracker-version (*M* = 6.16, *SD* = 2.26) and the Kinect-version (*M* = 5.77, *SD* = 2.17) all indicate rather an associative attentional focus. Data analysis shows a significant difference between the four versions of *Fit The Shape*, $F(3, 129) = 29.97, p < .001, \eta_p^2 = .41$. Post hoc comparisons reveal that ratings of attentional focus are significantly higher in the VR1PP-version and in the VR3PP-version than in the Tracker-version and in the Kinect-version (all $p < .001$), suggesting that associative thoughts were significantly more predominant in both VR-versions than in the non-VR-versions. No significant differences were found between the two VR-versions or between the two non-VR-versions.

Engagement

A Greenhouse-Geisser corrected repeated measures ANOVA determined that mean scores of the GEQ show a statistically significant difference between the four game versions, $F(2.51, 108.05) = 25.37, p < .001, \eta_p^2 = .37$. Post hoc comparisons reveal that the differences between the VR1PP-version (*M* = 47.09, *SD* = 10.82) and the Tracker-version (*M* = 39.50, *SD* = 11.22) as well as between the VR1PP-version and the Kinect-version (*M* = 37.62, *SD* = 9.87) were significant (both $p < .001$), indicating higher levels of engagement in the VR1PP-version than in the non-VR-versions. Additionally, engagement was significantly higher ($p < .001$) in the VR3PP-version (*M* = 46.11, *SD* = 11.27) than in the Tracker-version and the Kinect-version. However, pairwise comparisons between the VR1PP-version and the VR3PP-version and between the Tracker-version and the Kinect-version were not significant.

V. DISCUSSION

The main results of our study reveal immersion as the most influential construct compared to the player's perspective and the tracking fidelity by showing a significant difference between the VR- and non-VR-game for nearly every dependent variable. Considering the results of the performance, motivation, dissociation/association, and engagement a dichotomy of the values can be seen. For all constructs both VR-versions and both non-VR-versions do not show any differences within the groups but showed significant differences between them. Thus, the impact of VR and wearing an HMD on the player can be considered as important, influential factors for exergaming.

Our results reveal significant differences for all embodiment subscales between the VR- and non-VR-versions. Hence, VR seems to have a major impact on the sense of embodiment. Additionally, since *Body Ownership* and *Self-Location* show significant differences between the VR-versions the perspective seems to further influence the sense of embodiment. Since this difference was also recognizable for the experience of presence, it can be concluded that using a first-person perspective for room-scale VR exergaming which requires precise movements can be considered advantageous. This finding is consistent with the research of [12]. Thus, our results can be used for applications in which performing precise movements is an essential and vital part, such as in physical rehabilitation, where motivational lack is a central problem. Hence, we cannot support the statement that the experience of presence can occur equally, regardless of the perspective in VR environments [12], [19].

The performance results indicate a better performance in the VR-conditions which seems to be independent of the tracking fidelity since the non-VR-groups do not differ. Thus, it seems that proprioception was not considerably limited by wearing an HMD allowing the player to consider where her/his real body is in the virtual world and to perform precise movements. Furthermore, both VR-groups nearly significantly differ which indicates that the perspective seems to have an impact on the performance. This finding confirms that the first-person perspective can be useful for precise movements in VR. Since in the VR1PP-version the collision of the cubes occurred behind the camera, the question arises to which degree visual feedback is beneficial for the player and if the performance in the VR1PP-version could be further increased if feedback is displayed.

No differences were found for the perceived and physical exertion - thus, the exertion was similar regardless of the version, and the experienced exertion was nearly equal to the physical exertion. These results are contrary to the results of [23] and [38] since the perceived exertion was not lower than the physical exertion. Thus, the motivational increase and better performance in the VR-groups can be considered independent from the perceived exertion. This finding can be explained with regards to the task in the game. In *Fit The Shape* a precise movement was necessary, and thus the player was represented in the game via a virtual representation. Hence, the focus of the player was on her/his own body which leads to a realistic perception of the exertion. This idea is supported by the associate focus of the player in all groups. Although the VR-versions showed significant higher association values than the non-VR-versions, the perceived exertion was similar for all groups. Another interesting point we should consider is the possibility that the heart rate as an indicator for the physical performance does not adequately reflect the kind of exertion required by *Fit The Shape* and can further be affected by many other cues such as simulator sickness, excitement, or fun.

Since we have found no significant difference between the Tracker- and Kinect-version for any dependent variable it could be possible that the tracking fidelity between the two systems does not have an impact on any construct although the difference in the tracking resolution is huge: 30 vs. 120 HZ. Any possible impact of the higher tracking resolution could be equalized by two things. On the one hand, in the Tracker-variant we did not track every single joint but used inverse kinematics while the Kinect-variant tracks every single joint and thus achieves a more realistic motion capturing. On the other hand, wearing eight sensors while playing an exergame could have been experienced as disturbing and thus eliminating possible effects.However, after playing all game versions, when asked to indicate their preference for their movements being tracked using Vive Trackers or Kinect, 28 out of 44 participants stated they preferred Vive Trackers.

Although our results suggest that room-scale VR exergaming can positively impact the player and thus can be a considerable idea for therapeutic application the limitations of this approach have to be discussed. The success of prominent exergames is among other things defined by the simple controls the tracking system offers. Attaching tracking sensors and an HMD simply takes some preparation time and thus could be a huge barrier to even start with the game. Furthermore, wearing sensors on the body while playing can be considered unnatural, and it sometimes occurred that the sensors got out of place due to the physical movements. In the year of this investigation (2018), VR technology is not yet wireless. Thus, performing movements can be dangerous and requires participants to take care not to step on the cables. With new wireless generations of VR systems to come, this problem could be tackled.

For future applications and the use of room-scale VR exergaming future research should focus on the transfer of our results to a larger extent. Since the students in our study were physically rather fit and experienced with new technologies, the results have to be tested with a more diverse study group. Furthermore, although our results suggest that previous experience with VR seems not to impact the player's motivation and performance, the positive impact of room-scale VR exergaming can be a result of the novelty effect. Therefore, it has to be examined, whether room-scale VR exergaming is applicable for long-term use and can maintain long-term motivation.

VI. Conclusion

Our study indicates that room-scale VR exergaming can have a significant impact on the player's motivation, performance, presence, embodiment, and engagement. The most important and influencing variable in this context is immersion. Playing inside a fully-immersive virtual environment while wearing an HMD can have beneficial effects for the player and thus positively affecting physical exercising. In contrast to existing research, our application could not reduce the perceived exertion. We discuss this instance and point out that the task of the player in the game seems to influence the player's body perception and is thus a relevant factor for the perceived exertion. Our results further suggest that the tracking fidelity does not have any noticeable impact on the player. Since we only manipulated this variable for the non-VR-versions, future research should validate this finding for VR exergames.

Our work contributes to the understanding of the relationship of the most important constructs in the context of room-scale VR exergaming: motivation, performance, and exertion. Since exergames can be used to enhance physical activity, our results are particularly useful for future VR exergame applications aiming at helping people.

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Ghost Sweeper: Using a Heavy Passive Haptic Controller to Enhance a Room-Scale VR Exergame.

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***Abstract*—Virtual Reality (VR) exergaming is a beneficial and promising approach resulting from the combination of physical activity with the high motivation and enjoyment immersive VR offers. However, exergames can often fail to reach suggested levels of exertion. We, therefore, integrated a heavy passive haptic controller into a VR exergame. We explore the impact of the passive haptic controller and different kinds of kinesthetic feedback resulting from different interactions on the player experience. Our results of an extensive study (N=82) suggest, that using a heavy controller can significantly increase the exertion without reducing the motivation in contrast to using an HTC Vive controller. We discuss this finding in the context of haptic feedback and the experience of presence and the resulting implications for further research and VR exergames.**

***Index Terms*—Virtual Reality, VR, Passive Haptics, Controller, Exergame, VR Exergame, Exertion, Motivation**

I. Introduction

Exertion games or *Exergames* are digital games focusing on physical exercising. The authors of [25] define exergames as digital games "*[...] where the outcome of the game is predominantly determined by physical effort*". Exergames can have positive effects on the player's mood and emotional well-being [13] and can be used to support physical rehabilitation, psychological therapy as well as to prevent and counteract obesity [2], [12], [13], [22]. Furthermore, exergames can offer social benefits [19] and can even increase cognitive performance [11] in contrast to sedentary games.

In the context of exergames, immersion seems to have a vital impact on the beneficial effects exergames offer. Increasing the immersion in exergames can beneficially impact the training's intensity and motivation [5], [10] as well as the player's feelings of energy [29], and can lead to a better performance [5], [26] and reduced perceived exertion [23]. The highest degree of visual immersion can be offered by Virtual Reality (VR) systems featuring a head-mounted display (HMD). Hence, we refer to the term VR exergames as exergames including an HMD. A variety of current studies has demonstrated that creating exergames for VR is a promising approach and can beneficially impact performance, motivation, and presence [5], [18], [35], [40].

Among the parameters that determine the degree of immersion is the range of sensory modalities [36]. Hence, providing haptic feedback in virtual reality can significantly increase the experience of presence [9], [17]. This increase can also be found in the context of exergames, where it can beneficially impact the players' motivation and enjoyment [34], [39]. Haptic elements can further be used to increase the exertion of the players if they apply an exerting force-feedback to the players. Since exergames can fail to increase the level of energy expenditure [28] or may not contribute towards the recommended daily amount of exercise [14], integrating haptic feedback may be a promising approach. Thus, the exertion, as well as the immersion, can be increased at the same time. However, the resulting interaction of increased presence and enjoyment on the one hand and increased exertion on the other needs further investigation. In this paper, we, therefore, target the research question, whether using a heavy passive haptic controller can increase the players' presence, enjoyment, and exertion at the same time.

Hence, we implemented a heavy everyday object as a passive haptic controller into a room-scale VR exergame. Thus, we aim at achieving two effects. On the one hand, we aim at increasing the exertion due to the controller that weighs 594 grams. On the other hand, to counteract a potential motivational reduction that may result from high levels of exertion we further aim at increasing the immersion due to the haptic feedback our controller provides.

Our results of a study with 82 participants suggest that the integration of a heavy passive haptic controller can significantly increase the perceived and actual exertion of the player in contrast to the standard HTC Vive controller. We have also found a descriptively observable similar trend for the experience of presence. Further, the players' motivation values were not affected by the heavy controller and suggest that our setup was able to increase the exertion without reducing motivation. We further evaluate which haptic feedback cues are of particular importance for a VR exergame. Our work contributes to the design of (VR) exergames that aim at providing high levels of immersion, exertion, and motivation.

II. The Impact of Immersion In Exergames

Immersion can be defined as *"[...] the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant"* [38]. Hence, immersion can be seen as an objective characteristic of a technology, that describes the technical integration of a person into a virtual environment [36]. We distinguish between immersion and the user's experience of presence which can be seen as a direct consequence of immersion [37] and is often defined as *presence* or the feeling of "*being there*" [16]. In the context of exergames immersion has the potential to enhance the player experience.

The authors of [41] investigated the impact of an immersive VR-based exercise bike versus a traditional stationary exercise bike on the players' exertion, self-efficacy, and enjoyment. Their results reveal higher self-efficacy and enjoyment values for the VR condition. Since enjoyment is a vital actuator to act autonomously, it can maintain a long-term motivation [15] and is thus an important construct in the context of exergames. Further, the participants in the VR-exercise reported lower perceived exertion values though the physiological exertion did not differ between the groups. Hence, the VR condition acted as a distractor from the task and thus lowering the exertion while increasing the enjoyment. Similar results have been found by [3] who suggest that using an immersive 360-degree video with music while cycling has the biggest and most positive impact on the player compared to non-VR video and the exercise without any distraction. Furthermore, the authors of [1] have investigated to what extent VR can be used to enhance a rowing workout. For this, rowing athletes either trained with an HMD or traditionally without an HMD on a rowing machine. The results reveal that even for experienced athletes, the technique in VR could be improved and the VR condition was enjoyed more and resulted in higher distraction values for the athletes. These results are supported by the authors [32] who further suggest that using an HMD for rowing can enhance the workout more than using an immersive CAVE system.

Besides using VR as a distractor for monotonous exercises such as rowing or cycling, VR can also be used as a central part of the game. Here the required movements do not result from the training device but from the gameplay. The authors of [10] developed the immersive exergame *Astrojumper* that is played inside a three-sided stereoscopic cave system. The game does not aim at distracting the player from an exerting physical task but instead allows the players to focus on their body movements. The authors observed that high levels of motivation were accompanied by high levels of perceived exertion. Furthermore, the authors of [5] took a similar approach with their immersive exergame *Fit The Shape*. The authors systematically investigated the role of the output device, perspective, and tracking fidelity on the player experience. Their results suggest that in particular the output device (HMD) and perspective have the greatest impact on the player's motivation, presence, and performance. Further, the authors observed that the perceived exertion was not affected by any condition and concluded that the players' body awareness was not distracted by the game play setup.

A. Haptic Immersion

Among the parameters that determine the degree of immersion and thus the quality of experience is the range of sensory modalities [36]. Current VR exergaming research mainly focuses on the effects of auditory and visual stimuli [3], [5], [10], [32], [41]. However, so far, less research has been done on the effects of integrating haptics into exergames [21]. We distinguish between two types of haptic feedback. The *tactile feedback* describes the feeling of a touch that is perceived through the skin. *Kinesthetic feedback* describes a force acting on the body, which is measured by sensory cells or muscles [30].

The authors of [9] evaluated the effects of tactile cues on the player's presence by adding a fan and a heat lamp to their setup which were implemented meaningfully into their virtual environment. They found out, that the tactile cues had a great impact on the players and could significantly increase the experience of presence. Further, in [17] the authors enhanced a virtual environment with passive haptics. These objects which exist in the real as well as in the virtual world and thus can be touched were able to increase the experience of presence as well as the physiological arousal.

For non-VR exergames, the authors of [39] explored the impact of haptic feedback on the players' experience of presence. For this, they developed the exergame *Pedal Race* which was controlled by an exercise bike. The haptic feedback was provided by increasing the pedal resistance when the players entered a specific terrain in the game. The authors observed significantly higher presence scores for the haptic feedback condition and thus propose designers of future exergame should consider haptic feedback. In a more recent study [34] the authors evaluated the impact of haptic feedback on the players' performance, enjoyment, and motivation in a VR exercycle game. They integrated tactile feedback by adding a fan and kinesthetic feedback by increasing the resistance of the bike. The authors observed higher presence, motivation, and enjoyment scores for the tactile condition but only higher presence scores for the kinesthetic condition compared to a no-feedback condition. Yet, the authors did not assess the players' perceived exertion. However, integrating haptic feedback into VR exergames is a promising approach but has to be carefully considered with regards to the interplay of motivation and feedback type and the exertion resulting from it.

B. Contribution

Though exergames show a great variety of beneficial effects they can also fail to increase the level of energy expenditure

[28] or may not contribute to the recommended daily amount of exercise [14]. Several studies focused on the question of how the exertion in exergames can be meaningfully increased. The authors have either increased the necessary movements of existing Wii games [24], made the visual appeal of the game dependent on the exertion [7] or improved the skills of the players' avatar if they trained in a corresponding heart rate range using a recumbent bicycle [20]. In our paper we take a different approach and make use of haptic elements. On the one hand we use a heavy passive haptic controller to increase the exertion. However, we do not want to reduce the players' motivation and thus leveling the reason for playing an exergame due to the high exertion. Hence, we further aim at increasing the immersion and hence the motivation by providing meaningful kinesthetic feedback on the other hand. We investigate the impact of our setup on the interplay of presence, motivation, enjoyment, and exertion to gain new insights on how haptics can be integrated into VR exergames.

III. Ghost Sweeper

The exergame *Ghost Sweeper* serves as the basis for the study presented in this paper. *Ghost Sweeper* was developed using the game engine *Unity*. Since we want to systematically investigate the effects of an exerting passive haptic controller we implemented three different versions of the game each offering a different type of haptic feedback.

The basic gameplay is identical in each version. The player is located inside a haunted medieval castle. The player's goal is to defend the castle from the ghosts which haunt the castle. For this, the player is equipped with a special energy broom. As shown in figure 1 we have used a common corn broom to which an HTC Vive tracker is attached. Grip tape was wrapped around the broom handle to increase the grip. We then created a virtual replica of the original broom which serves as the interaction device and has the same dimensions as the real one. Further, all movements of the real-world broom are mapped to the virtual one. The player interacts with the game using only the broom. In total the broom and the attached components weight 594 grams and are thus twice as heavy as a common tennis racket. As the output device, we use the wireless version of the HTC Vive.

We have decided to use an everyday object as a passive haptic interaction object. On the one hand, we have thus focused on the integration of simple objects to show that complex technical setups are not required and games can be easily enhanced. On the other hand, due to the broom's soft end, the broom can be hit on the floor without risk. This makes it easy to realize kinesthetic feedback. With other sports equipment, such as tennis rackets or baseball bats, this would not have been possible without several risks.

The dimensions of the play area are 3 * 2.5 meters. Inside this area a green circle is displayed at the ground and serves as an energy field. To destroy a ghost, the player must

Fig. 1. **A** The real world broom has a length of 135 centimeters. An HTC Vive tracker is attached to the broom using a clamp. In total the broom weighs 594 grams. **B** The virtual broom has the same dimensions as the real one. A virtual tracker model is attached to the broom and acts as a visual indicator displaying whether the energy shock can be used (green light vs. red light).

perform a downward movement with the broom and hit the ghost on the head and then the green circle within the same movement. The interactions with the broom and the ghosts are only registered if the player hits the energy field after hitting a ghost. Thus, we can ensure that the player hits the ground in the real world and hence receives kinesthetic feedback. Further, the green circle acts as an indicator where the player can hit and thus reduces the risk of hitting real-world objects. Further, the players can also generate an energy shock by turning on their axes while pressing the broom to the ground. This shock will freeze the movements of all ghosts for six seconds and has a cooldown time of 20 seconds.

There are four types of ghosts differing in their speed and number of hits they can withstand. As shown in figure 2, if a ghost gets destroyed it will shatter into pieces and the player receives a score based on the required effort to destroy the ghost. The player's score is displayed on a table inside the virtual environment. To avoid demotivating game elements, the player can not lose points nor lose the game. Each game lasts three minutes. Ghosts immediately start to spawn when the game begins. We deliberately chose a high spawn rate to ensure that the player is always busy and does not have resting breaks. Thus, the three minutes can be seen as a short high-intensity exercise.

To investigate which impact the haptic controller and the kinesthetic feedback resulting from the interactions have on the player, we implemented three different versions of the game, which are presented in figure 3. In the *Broom-Ground* condition, the player has to hit the ground using the real broom

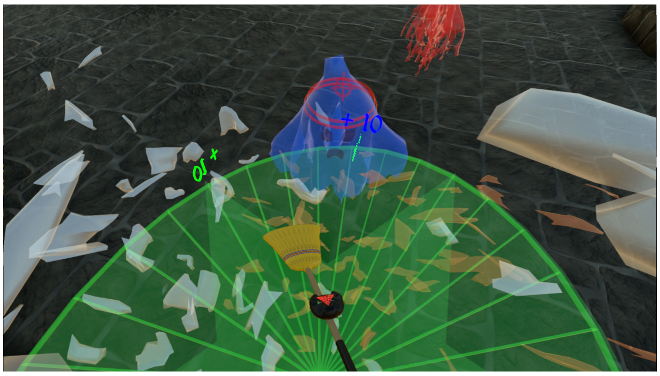

Fig. 2. *Ghost Sweeper* is played from a first-person perspective. In this screenshot the player just destroyed a ghost using the virtual broom. The red light on the virtual Vive tracker indicates that the player needs to wait until the energy shock can be used again.

to destroy the ghosts. Thus, the player experiences a force-feedback when the broom hits the floor. To investigate the impact of the haptic feedback which is provided by hitting the floor, we created the *Broom-Air* condition, in which the green energy field is moved up half a meter. Hence, the player does not need to hit the physical ground and thus does not receive the same force-feedback as in the *Broom-Ground* condition. To further investigate which impact the physical broom has on the player, we created a *Controller* condition, in which the player interacts using an HTC Vive Controller. In this version, we also use the virtual broom representation and display the green energy field on the ground. We deliberately neglected to implement a fourth version with an HTC Vive Controller and an energy field that is moved up since the player would not experience any force-feedback in both conditions.

IV. Evaluation

We conducted a comprehensive study to investigate the impact of the passive haptic controller on the one hand and the impact of the force-feedback provided by hitting the ground on the other hand.

A. Method

We used the Borg Scale [4] to assess the perceived exertion. The scale ranges from 6-20 (none - very, very hard). The scale is based on the assumption that a person has a resting pulse of 60 beats per minute and that the perceived exertion correlates positively with the actual heart rate. Hence, the heart rate can be estimated by multiplying the Borg value with 10. The actual exertion was measured using the heart rate which we measured using the *Bittium Biosignals Ltd. Faros 180* pulse belt.

Furthermore, we measured the participants' dissociation and association to assess whether our setup distracted the players' attention. Congruent with the research of [23] association is defined by a focus on internal body stimuli whereas dissociation is defined by a focus on external stimuli and distance to internal body stimuli. This attentional focus could be rated on a scale from 0 (dissociation) to 10 (association).

We used the Intrinsic Motivation Inventory (IMI) to measure the players' motivation. The inventory consists of six subscales of which the *Interest/Enjoyment* subscale is considered the most significant since it directly measures intrinsic motivation [8]. The experience of presence was measured using the *IGroup Presence Questionnaire* (IPQ) [33]. The IPQ comprises the one-item subscale *General Presence* and three further subscales *Spatial Presence, Involvement, and Experiences Realism*.

Since the players' sportiness can moderate the assessment of the exergame, we used the International Physical Activity Questionnaire (IPAQ) [6] to assess the daily physical activities of the participants.

B. Design and Procedure

We used a between-subject design in our study. Hence, every participant played one of the three versions of *Ghost Sweeper*. The participants were assigned randomly to one of the conditions. The same dependent variables have been assessed in each of the conditions. Before the start of the experiment the participants gave their consent and put on the pulse belt while the instructor waited outside the laboratory. Afterward, demographic data, the IPAQ, and experiences with digital games and VR were assessed. Subsequently, the participants were asked to sit on a sofa for five minutes so that a resting pulse serving as a baseline measurement could be recorded. After finishing the resting period, the participants put on the wireless HTC Vive and received the controller. A short tutorial introduced the game world as well as the interactions and automatically started the actual game afterward. During the gameplay we recorded the heart rate of the participants to evaluate the physical exertion of the participants. The participants played the game for three minutes. Subsequently, the participants filled out the remaining questionnaires. After completing the last questionnaire, the subjects were debriefed about the experiment. The complete experiment lasted 45 minutes in total. The ethics committee of our university approved the experiment.

C. Hypotheses

Based on the assumption, that the broom controller is heavier and provides more haptic feedback than the HTC Vive controller, we hypothesize that

I *Participants playing with the real broom show higher exertion and presence values than interacting with the Vive controller.*

We further assume, that the Broom-Ground condition provides the most haptic feedback and therefore hypothesize that

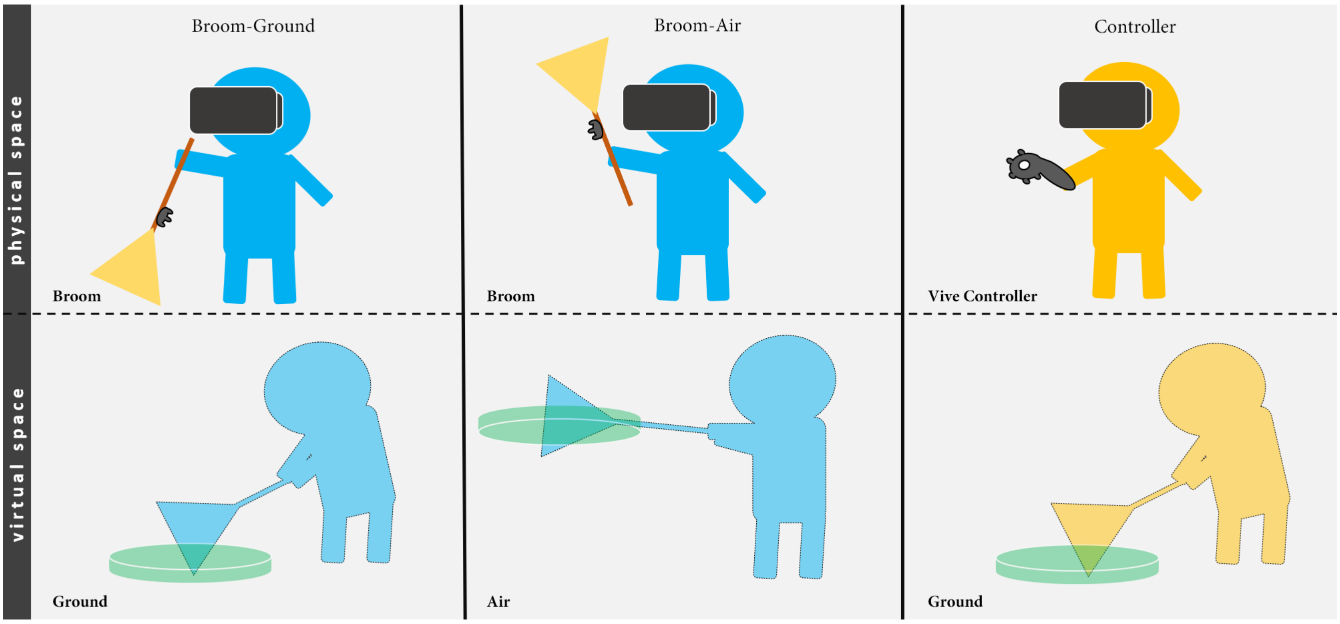

Fig. 3. Three different versions of the game were implemented which differ in the controller used and the position of the virtual ground. In the Broom-Ground condition the player interacts using a real broom. Here the virtual ground is at the same position as the real ground. In the Broom-Air condition, the player also interacts using the real broom but does not need to hit the real ground, since the virtual ground is moved into the air. In the Controller condition, the player interacts using a controller but sees a virtual broom. Here the virtual ground is also at the same position as the real ground.

II *Participants in the Broom-Ground condition show higher presence values than in the Broom-Air condition.*

Since current research showed that a strong connection between presence and motivation exists we further hypothesize that due to the higher hypothesized presence values between all conditions

III *The participants' motivation differs in all three groups and show the highest values in the Broom-Ground and the lowest in the Controller condition.*

D. Results

69 female and 13 male participants were included in the analysis $(N = 82)$. 28 subjects were assigned to the Broom-Ground condition and 27 each the other two conditions. The age ranges from $17 - 32$ years $(M = 21.24, SD = 3.29)$. 50% of the participants reported having played an exergame at least once. The VR experience can be rated low with 79% of the participants having no or just a little experience with VR systems. After removing outliners from the IPAQ the athletic activity of the participants was categorized. 9 participants were categorized as low, 48 as medium, and 19 as high.

One-way ANOVAs were calculated for the following comparisons of the dependent variables between the groups. According to [31] if the groups consist of $N \geq 25$, ANOVAs are robust against violations of the normal distribution, which is why we did not check for normal distribution. Furthermore,

TABLE I
MEANS AND STANDARD DEVIATIONS OF THE DEPENDENT VARIABLES

Subscales	Broom-Ground M *(SD)*	Broom-Air M *(SD)*	Controller M *(SD)*
Exertion			
HR gameplay	133 (*17.5*)	123 (*16.4*)	111 (*17.6*)
HR difference	44.5 (*17.1*)	38.4 (*12.3*)	27.7 (*13.6*)
Borg	13.3 (*1.65*)	12.9 (*1.42*)	10.5 (*1.93*)
Attentional Focus			
Diss-&Association	5.32 (*2.75*)	5.56 (*2.90*)	3.15 (*2.52*)
IPQ			
General Presence	4.71 (*1.05*)	4.70 (*1.14*)	4.04 (*1.29*)
Spatial Presence	4.63 (*0.90*)	4.67 (*0.99*)	4.25 (*1.13*)
Involvement	4.36 (*1.01*)	3.52 (*1.07*)	3.50 (*1.31*)
Experienced Realism	1.95 (*0.83*)	2.12 (*0.78*)	1.70 (*0.62*)
IMI			
Interest/Enjoyment	5.83 (*1.00*)	6.02 (*1.07*)	6.00 (*0.90*)
Perceived Competence	4.43 (*1.11*)	4.33 (*0.99*)	4.91 (*0.78*)
Effort/Importance	5.26 (*1.01*)	5.50 (*0.85*)	4.93 (*0.99*)
Pressure/Tension	4.34 (*1.12*)	4.27 (*1.03*)	3.21 (*1.11*)
Perceived Choice	5.16 (*1.08*)	4.95 (*0.95*)	5.20 (*0.96*)
Value/Usefulness	4.30 (*1.22*)	4.23 (*1.30*)	3.48 (*1.41*)

variance homogeneity according to the Levene test was given for all dependent variables. If significant differences between the conditions were found, Bonferroni post hoc tests were calculated. The descriptive values for all dependent variables are shown in table I. The results of the inferential statistical evaluations are presented in the following subsections.

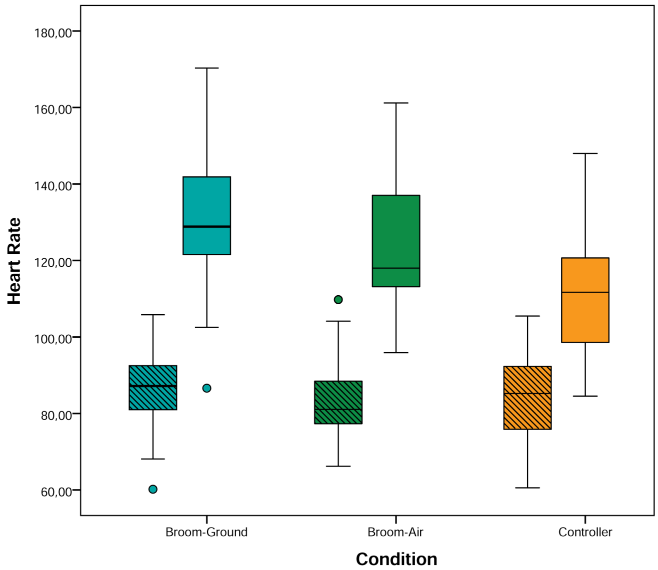

Fig. 4. The hatched areas represent the respective heart rate baseline measurements. The unhatched areas represent the respective average heart rates during the gameplay.

1) Exertion: To compare the physical exertion which is presented in figure 4 we calculated the heart rate difference for each participant between the average heart rate during the gameplay and the average heart rate during the baseline measurement. We found a significant difference for the resulting value between the groups $F(2,79) = 9.29, p < .001, \eta_p^2 = .19$. Post hoc comparisons revealed a significant difference between the *Broom-Ground* and *Controller* condition ($p < .001$) as well as between the *Broom-Air* and *Controller* condition ($p = .025$). No significant difference between the Broom conditions was found. Regarding the perceived exertion, the results suggest a similar tendency as for the physical exertion. A significant difference for the Borg value between the groups was found $F(2,79) = 21.91, p < .001, \eta_p^2 = .36$. Post hoc comparisons indicate significant higher scores in the *Broom-Ground* condition compared to the *Controller* condition ($p < .001$) and in the *Broom-Air* condition compared to the *Controller* condition ($p < .001$). No differences were found between the Broom conditions. The Borg values for both Broom conditions indicate a somewhat hard exertion whereas the values for the Controller condition indicate a fairly light exertion.

In a next step, we calculated the individual percentage of the maximal heart rate by dividing the heart rate during the gameplay by the individual maximal heart rate (220 - age). If we compare the individual relative heart rate with the relative Borg value (Borg value divided by the maximal Borg value) no significant difference is observable. This indicates, that the participants were able to rate their perceived exertion precisely. Further, in the *Broom-Ground* condition 60% , in the *Broom-Air* condition 30% and in the *Controller* condition 22% of the players reached a moderate or high intensity level according to the intensity levels of the ACSM [27]. The findings are further supported by the the results regarding the dissociation and association values which reveal a significant difference between the groups $F(2,79) = 6.44, p = .003, \eta_p^2 = .14$. The players in the *Broom-Ground* condition ($p < .012$) and in the *Broom-Air* condition ($p < .005$) had a significantly higher associative focus compared to the *Controller* condition.

2) Presence: A significant difference for the *General Presence* subscale was missed $F(2,79) = 3.04, p = .053, \eta_p^2 = .07$. Descriptively considered, however, a dichotomy can be identified with higher values in both broom conditions than in the *Controller* condition. Further we have found a significant difference for the *Involvement* subscale $F(2,79) = 5.17, p = .008, \eta_p^2 = .12$. A post hoc comparison revealed higher values for the *Broom-Ground* condition compared to the *Broom-Air* ($p = .022$) condition and compared to the *Controller* condition ($p = .019$). No other significant differences were found for the remaining subscales of the IPQ.

3) Motivation: The overall results of the IMI show high average values in all subscales. Especially the values for the most significant subscale *Interest/Enjoyment* are very high but do not differ between the conditions. Overall ANOVAs revealed significant differences for the *Pressure/Tension* $F(2,79) = 9.18, p < .001, \eta_p^2 = .19$ and *Value/Usefulness* $F(2,79) = 3.31, p = .042, \eta_p^2 = .08$ subscales. However, post hoc comparisons only revealed significant differences for the *Pressure/Tension* subscale with higher values for the *Broom-Ground* condition compared to the *Controller* condition ($p = .001$) and *Broom-Air* condition compared to the *Controller* condition ($p = .002$). We have further observed interesting correlations between the *Interest/Enjoyment* subscale and the subscales of the IPQ. The *General Presence* $r(82) = .325, p = .003$, *Spatial Presence* $r(82) = .462, p < .000$, and *Involvement* subscale $r(82) = .247, p = .025$ highly correlate with the *Interest/Enjoyment* subscale of the IMI and thus indicate, that presence and motivation are linked closely. Surprisingly, we have found no correlation between the actual exertion and perceived exertion with the *Interest/Enjoyment* subscale.

4) Sportiness as a confounding variable?: To investigate whether the participants' sportiness is a confounding factor, we calculated correlations between the *IPAQ* score and all subscales of the *IMI, IPQ, BORG*, and the heart rate difference. We found no significant correlations. Hence, the results seem independent of the physical activity of the participants.

V. Discussion

Our approach was to increase the exertion in an exergame in such a way that the motivation and enjoyment are not reduced. Our results reveal that the integration of an exerting passive haptic controller can significantly increase the perceived and physical exertion in contrast to an HTC Vive controller. In the Broom-Ground 60% of the participants reached a moderate or high-intensity level and thus twice as many as in the Broom-Air condition and nearly three times as many as in the Controller condition. Since the ACSM and world health organization guidelines suggest to train at least 150 minutes a week at a moderate intensity or 75 minutes at a high intensity especially the Broom-Ground condition can contribute to reaching these goals. We further aimed at increasing the players' presence by providing rich haptic feedback. Our results indicate that there is a tendency towards higher general presence values in the broom groups. Hence, our first hypothesis can be confirmed for the exertion part but only partly confirmed for the presence part.

We have found significantly higher *Involvement* values for the *Broom-Ground* condition compared to both other conditions. This finding is interesting since it could be an indication of a confirmation of our second hypothesis. We assumed that the kinesthetic feedback resulting from striking the ground is more intense and thus provides a higher sense of presence than hitting in the air. However, no other subscale shows the same tendency as the *Involvement* subscale. Thus, we have to reject our second hypothesis. The difference in the kinesthetic feedback between the broom conditions is so marginal, that it seems to have only little influence. In addition, it happened that also in the *Broom-Air* condition, the players hit the real ground.

Surprisingly we have found no difference between the conditions for the *Interest/Enjoyment* subscale. Hence, we reject our third hypothesis. However, the enjoyment values for all conditions are really high. Thus regardless of the version, the participants enjoyed the game. Further, though the broom conditions show higher exertion values, the motivation in these conditions has not been reduced. Hence, we achieved our initial goal to increase the exertion without negatively affecting motivation. In this context the *Pressure/Tension* values are interesting since they reveal higher scores in both broom conditions compared to the controller condition. Since this subscale is theorized to be a negative predictor of intrinsic motivation [8], we see our assumption that a higher exertion can have a negative motivational impact to be confirmed.

However, as we found no difference in the motivation between the groups and no correlation between the *Interest/Enjoyment* subscale and the participants' exertion, the negative influence of the exertion on the motivation seems to have been compensated. We assumed that a higher sense of presence due to the kinesthetic feedback resulting from the broom controller and the related interactions would counteract a potential motivational loss. Since we have found positive correlations between three subscales of the *IPQ* and the *Interest/Enjoyment* subscale of the *IMI* the assumption that a higher sense of presence leads to higher motivational values seems to be confirmed. However, we have found no significant differences between the broom conditions and the controller condition for the IPQ subscales. Thus it is possible that the descriptively observable difference in the presence values influenced the motivation, though no statistical difference was found.

The values of the attentional focus further indicate that the participants had a stronger body perception with increasing exertion. As planned, our application, therefore, did not distract from the actual exertion. In line with [10], high exertion values are accompanied by high motivation. Thus, using room-scale VR setups for exergaming is a promising approach for future developments to achieve high levels of motivation that seem to be independent of the exertion.

Although our results are promising and can be used for the design of future exergames we have to discuss some limitations. We observed, that the participants in both broom conditions tend to report that interacting with the broom in both conditions led to uncomfortable postures. Although this does not seem to influence the motivation, future developments should choose a more posture pleasant interaction. Further, the game only lasted for three minutes. This period may be too short for a meaningful assessment of the perceived exertion. Future developments should aim at evaluating whether the high motivation values are also observable for longer gameplay or more consecutive rounds. However, 83% of the participants in our evaluation would have liked to continue playing the game and even 48% of the participants would have liked to play for another five minutes. Furthermore, using a common broom to interact in a VR game is simply something new and could, therefore, trigger the novelty effect.

VI. Conclusion

Our study indicates that integrating an exerting passive haptic controller into a VR exergame can significantly increase the perceived and actual exertion without reducing the motivation. The haptic feedback provided by the passive haptic controller could not increase the experience of presence significantly, though a positive trend is observable. Since the exertion tends to increase the pressure and tension of the player but did not reduce the motivation and since we found positive correlations between the players' motivation and the experience of presence, we nevertheless assume, that a potential motivational loss due to the higher exertion was counteracted by the rich haptic feedback the passive haptic controller provides.

Our work contributes to the future design of VR exergames which aim at providing high levels of exertion and motivation/enjoyment at the same time. Furthermore, since room-scale VR gaming becomes increasingly popular, our approach serves as an easy realizable possibility to expand current games which then can offer an increased exertion mode.

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Co-Located vs. Remote Gameplay: The Role of Physical Co-Presence in Multiplayer Room-Scale VR.

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Abstract—**Our research investigates the role of physical co-presence for the experience of multiplayer cooperation in virtual reality (VR). We developed and compared a shared-room (co-located) and separated-room (remote) version of a cooperative two-player VR game. In an extensive study (N=92) we assessed measures of task awareness and spatial presence, as well as player communication, interaction, and performance. Our results indicate that players sharing the same physical space tend to neglect the cooperative task. Moreover, our results indicate that being physically separated can beneficially impact the perceived cooperative social presence, quality of communication, and performance in contrast to sharing a physical space. The role of physical co-location in room-scale VR and potential confounding effects caused by it, as well as implications for further research, are discussed.**

Index Terms—**Virtual Reality, VR, Co-Location, Co-Presence, Collaboration, Cooperation, Shared Space, Multiplayer**

I. Introduction

Modern VR technology enables people in professional as well as entertainment domains to interact simultaneously in those worlds, even if they are physically apart. However, technological advancements in the development of head-mounted displays (e.g., standalone devices) eventually lead to a growing number of use cases, that easily allow multiple co-located users to interact in a shared virtual world. Such use cases include games for entertainment (e.g., The VOID) and serious applications for teams alike. Thus, knowledge of the psychological and behavioral consequences of being virtually and physically co-located at the same time would enhance the design of such applications.

The role of physical co-presence was previously investigated in the context of digital multiplayer games as a component of the overall social setting, [4], [8], [11]. Although in traditional co-located hardware setups player focus should rather be on the shared screen than on each other, the physical co-presence of others seems to beneficially impact the overall player experience, either due to the mere fact of being co-located or due to social interaction as a consequence of sharing a physical space (see [4] for review on this topic). Compared to remote multiplayer games, co-located games are assumed to provide a higher sense of social presence (“the sense of being together with another” [3]), and thus, increase enjoyment under certain circumstances [8]. Furthermore, persons playing in co-located settings tend to report greater involvement, engagement, competence, and positive affect, as well as lower tension, [4], [7], [8].

In VR settings the question arises whether the same tendency for remote and co-located gameplay is observable since modern HMDs can fade out the real surrounding and thus the other player. Gómez and Verbeek [1] addressed this question using cardboards which do not support room-scale. Their results indicate that cardboard VR technology can equalize the experiences of playing co-located and remotely. However, sharing the same physical space in modern room-scale VR systems enables new ways of experiencing the other player (i.e., colliding). Podkosova and Kaufmann [14] examined in a more recent work the impact of a multi-user navigation task in room scale VR. Their results indicate that sharing the same physical space can lead to undesirable effects such as a reduced focus on the task.

To shed more light on the relationship between physical co-location and player experience in VR contexts, we extended previous research and compared a co-located and remote version of a two-player VR game. We conducted a study with 92 participants in a between-group design and collected several player experience related constructs. Our results indicate that the perceived cooperative social presence, performance measures, and the perceived quality of communication are higher in the remote setting than in the co-located setting. Hence, playing in the same space in multi-user VR can be disadvantageous if not considered carefully. Our work contributes to the understanding and future design of multi-user VR applications. We address game designers and researchers alike who seek to create multiplayer VR applications by pointing out benefits and limitations which result from multiplayer room-scale VR.

II. Related Work

A. Designing Multiplayer VR

Physical co-location introduces specific challenges to the design of VR multiplayer games. Therefore, the specific approaches to overcome those challenges determine how the player experience is affected.

As long as wired HMDs are the common hardware, cable management should be considered in general and specifically in co-located settings as a potential source of interference for gameplay. To a certain degree the tangling up of cables can be prevented by construction-based characteristics of the play space (e.g., placement of computers the HMDs are connected to, trusses). However, as long as the interactions within the virtual world require players to move around in various directions, these approaches are not sufficient. Therefore, the characteristics of the virtual world should be thoroughly considered in the game design process.

Two challenges in the design of co-located multiplayer VR interaction are the phenomenon of spatial desynchronization (when players are in physical proximity but virtual distance) and techniques for collision avoidance. If co-located players share a limited physical space but explore a larger virtual world, spatial desynchronization could occur [13]. This desynchronization threatens the general spatial orientation, and thus player safety, by provoking physical collisions. The issue of spatial desynchronization is based on the general possibility of physical collisions in co-located multi-user VR and its impact on user interaction. The authors of [14] compared a co-located and remote setting of a navigation task regarding users collision avoidance behavior. Results indicate that physical co-location impacts user behavior and user attention processes. Specifically, being co-located during interaction in VR led to a reduced focus on the task and an increased focus on collision avoidance, which is also reflected in greater clearance distances between users [14]. In summary, if applications do not implement a specific strategy against collisions, users tend to actively focus on it by themselves, eventually reducing the focus on the actual task of the interaction. Nevertheless, merely limiting the individual movement to smaller spaces may lead to dissatisfaction with the overall experience as reported in [13], and thus seems not a desirable approach. Although the findings in [14] regarding the shift in user focus are comprehensible, further work must verify if this shift applies in other, more engaging interactions. Based on their research question, the authors of [14] implemented path crossing, thus collision avoidance behavior, as an integral part in their experimental design. However, VR games are not limited to navigating through physical space, as they can have a variety of objectives and challenges. Therefore, it has yet to be validated, if VR multiplayer is affected by potential physical collisions, if the mere navigation is not the central objective.

In contrast to this rather negative perspective on body contact during VR interaction, providing remote VR users with additional sensory information cues (e.g., tactile cues of proximity) has found beneficially impact mutual awareness and certain aspects of cooperation [17], [18]. Whereas [17], [18] did not directly compare co-located and remote interaction in VR, their work indicates, that co-located settings may have certain advantages over remote settings.

An approach to investigate physical co-presence in multiplayer VR independent from collisions is described in [1]. The authors investigated the impact of physical co-location on game experience and social presence in a two-player VR game. In contrast to [14], they used a seated VR experience with cardboard HMDs. Referring to research on social presence in digital games, they argue that information cues like sounds of physical movement might enhance social presence in a co-located setting, although users are immersed visually and auditory. Interestingly, the two settings did not differ regarding the social experience. The authors conclude that the visual immersion of the cardboards, as well as the possibility to speak with each other (directly or via voice chat), equalize the experience and thus limit the potential impact of other consequences of physical co-presence [1].

B. Researching Multi-User VR

If the physical presence or absence of a co-user impacts aspects of interaction experience and behavior in VR contexts differently, then research in this domain should consider the spatial setting as a potential confounding factor in experimental designs. Review of related work indicates that the decision of co-location or separation of users in experimental settings is influenced by various factors, that are not always explained in detail or reported at all (e.g., confounding effects by meeting of participants before the actual interaction in VR [2], [9], technical setups or hardware limitations [20], not reported [5]). Therefore, we also review previous work, where authors discuss the role of physical co-presence or work that could benefit from considering it as a potential confounding factor.

The role of physical co-presence was previously partly discussed in the context of research on approaches to advance virtual interaction [16], [20]. In [20] the authors compared different techniques of gaze simulation behavior for user avatars. They investigated a two-user co-located VR setting and assessed various measures of the interaction experience (i.a. involvement, co-presence). In their discussion, they identify the awareness of being co-located as a potential confounding factor for involvement and suggest to compare presence-related aspects and quality of communication between co-located and remote users in future research. They support their discussion by comparing their findings to previous related work [9] that examined gaze behavior in a remote setting.

The work of [16] is another example for the discussion of the spatial relationship of VR users as a potential influencing factor. The authors investigated how they could visualize social behavior cues (i.e., joint attention, eye contact, and grouping) in a large-scale co-located VR setting, where participants were asked to explore a virtual museum. The comparison of an augmented and a non-augmented condition indicates that social augmentations enhance social perception and behavior. However, the authors did not find differences regarding certain measures of co-presence. Since users could hear each other in the physical space, and thus could estimate their physical social surrounding, the physical co-location in the setting is discussed as a potential confounding factor for potential effects of social augmentations.

The review of related work on multi-user VR should highlight two aspects. First, the role of physical co-presence has not been consistently considered as a potential influencing factor regarding various research questions. Second, previous studies directly comparing co-located and remote settings are either limited in the hardware they used when compared to current consumer devices [1] or limited regarding the complexity and engagement of interaction [14]. Therefore, we extend these approaches by comparing a co-located and a remote version of a self-developed multiplayer VR game as described in the following sections. Thus, our work contributes to the general research on multi-user VR, as well as to the design of multiplayer VR games.

III. VR Multiplayer Testbed Game

We developed a testbed game to investigate the role of physical co-presence in multiplayer VR. It is a cooperative two-player game, in which players are wizards that defend their tower of knowledge from being plundered by monsters. Those monsters try to steal the books that are inside the tower by sneaking in and bringing them in the surrounding forest (see figure 1). The players are positioned on the top of the tower, whose virtual size corresponds to the available physical play space. The walkable virtual area is limited to this space. Thus, players can freely move around based on natural walking without worrying about spatial desynchronization [13]. In order to not provoke virtual and physical collisions, the gameplay does not require extensive movements around the play area. Thus, we purposefully decided against dividing the play area into two individual parts in line with [13]. Therefore, we deliberately decided that collisions between the players are possible to evaluate which impact collisions and potential collision behavior have on the player experience and cooperative social presence. Players are represented by the same virtual model, consisting of an HMD wearing a wizard hat, indicating their heads positions in physical space. Additionally, one hand of each player is represented by a wand, whose position corresponds to the Vive controller movement of a player in physical space (see Figure 2).

On top of the tower, the players see waves of monsters approaching from the surrounding forest. Monsters belong to one of three types, that differ in their movement, size, speed, defense, and their ability to swim. Small enemies are faster but withstand fewer hits than bigger ones. Additionally, blue enemies can swim through the moat to reach the tower. When a monster reaches the tower by one of the bridges or by the moat, it turns around and heads back to a random position in the forest. Once it reaches the forest, the books it stole are lost. The players have to stop them by shooting magic projectiles on them. This is done by pressing the trigger button on the Vive controller. If a player defeats a monster that carries books, the books are dropped at the position of its defeat. To recollect dropped books players can command an owl that rests in a cage underneath the top of the tower. By pressing the controller trigger while pointing at the cage, the owl flies to the battlefield and randomly collects up to ten books. Once returned, and after a 30 seconds cool-down the players can command the owl again.

Additional to individually shooting the enemies, players can coordinate two types of cooperative attacks. The first is triggered by hitting a monster with two successive hits from both players within a time frame of two seconds and quintuples the damage. The second cooperative attack is a thundercloud, that deals area damage and can defeat several enemies at once. A control panel for generating the cloud is attached on the back wall of the playing area (see Figure 2). Thus, the players are required to decide when they should use individual, that are fast or cooperative attacks, that require them to coordinate their actions but are more effective in certain situations.

Each game lasts nine minutes. In total 193 monsters are spawned in waves at predefined points in time. If players defeat a wave before the next one is spawned, they must wait and can recollect lost books. The number of stolen books and defeated enemies are displayed on the back wall of the playing area.

Due to hardware and performance limitations, it is common that only one HMD can be connected to a VR computer at a time. Therefore, multi-user VR applications are generally networked applications, independent of the spatial setting. Thus, it was not required to design the game specifically for co-located or remote players. The described game was played either in a shared physical space or in different rooms, without any further specific adaptations of the game design. We defined tracking areas identical in size in both scenarios with the *Steam VR Room Setup*, to ensure comparability as well as congruency between the position in virtual and physical space.

IV. Evaluation

We conducted a comprehensive user study to explore the impact of physical co-presence in a room-scale VR multiplayer game on cooperative social presence, spatial presence, performance, as wells as quality and quantity of communication, and the number of cooperative interactions. Hence, we compared a co-located and a remote session of gameplay of the same game.

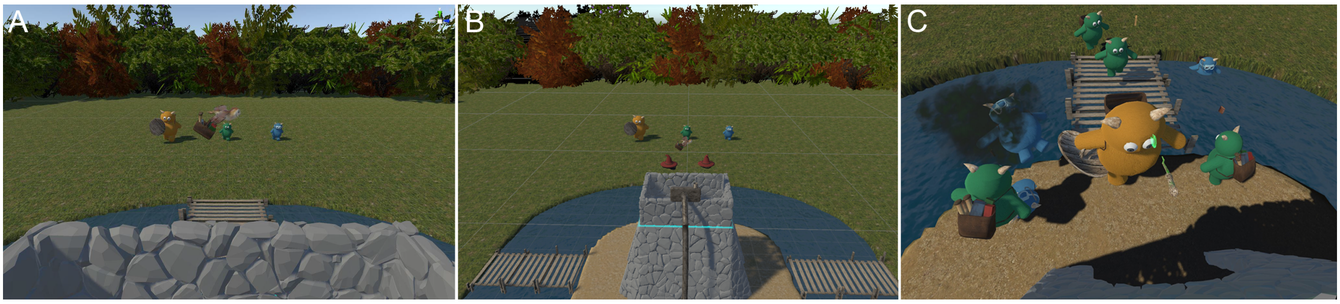

Fig. 1. **(A)** Three different enemies are approaching the tower as seen from a player's perspective- **(B)** The tower the players are standing on is surrounded by a moat which only the blue enemies can pass. The others must cross the bridges. **(C)** A player's perspective during the actual gameplay shows several enemies which are approaching the tower to steal books.

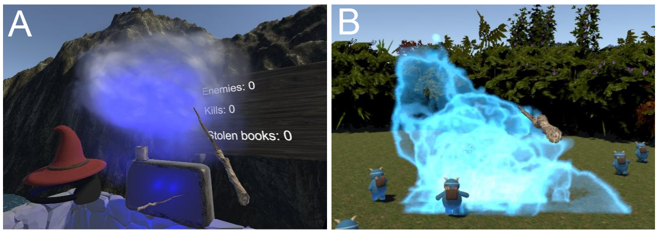

Fig. 2. **(A)** One player creates a cloud by sliding over the control panel with his wand. The other player can now move the cloud to the desired location on the battlefield by pointing her/his wand correspondingly. **(B)** After the second player has moved the cloud to the desired position, the first player can shoot the cloud to detonate it, defeating all monsters in a certain radius.

Based on the literature research we hypothesize the following:

I *Playing in a co-located space leads to a reduced task awareness than playing in a remote setting*

We further assume that a shift in the task focus might lead to reduced performance and additionally lowers the perceived quality and quantity of communication as well as the number of cooperative interactions in the co-located condition. We, therefore, further hypothesize the following:

II *Playing in a co-located space leads to lower*
  a) Communication quality
  b) Communication quantity
  c) Performance
  d) Number of cooperative interactions

A. Measurements

1) Cooperative Social Presence and Spatial Presence: Since our game is a cooperative, team-based game, with cooperation as the main task and objective, we assessed task awareness among teammates during gameplay, with the Co-operative Social Presence (CSP) sub-scale of the *competitive and cooperative presence in gaming questionnaire version 1.2* (CCPIG) [10]. It is designed for the evaluation of team-based digital games and is divided into the two dimensions *Perceived Team Cohesion* and *Team Involvement*. Team cohesion represents the level of perceived effectiveness and successful cooperation of the team. Team involvement refers to the degree of team involvement, team investment, and dependency on a team. Playing with other persons has an impact on the experience of spatial presence [15], and in the CLS condition, a mismatch between the virtual and physical representation of the other player could be possible and hence break the illusion of being located in a virtual environment. We therefore observed the experience of spatial presence using the *igroup presence questionnaire* (IPQ) [19]. The IPQ consists of four subscales: *spatial presence, involvement, experienced realism, and general presence*.

To evaluate the experience of collision avoidance behavior, we formulated the following three questions that were required to be rated on a five-point Likert scale:

- *Did the presence of your teammate restrict your freedom of movement?*
- *Did you deliberately avoid physical contact with your teammate?*
- *How much did you pay attention to where your teammate was and what she/he was doing?*

2) Communication and Interaction: We assessed two aspects of player communication - quality and quantity. To examine the quality of communication, we formulated five items which should be rated on a five-point Likert scale. The questions covered the subjective experience regarding the efficiency of the communication, e.g., *(My teammate directly understood what I was trying to tell her/him)*. We calculated one resulting *qualitative communication score* by adding all scores of the items. To assess the quantity of communication, we used an objective approach by recording the verbal communication of each game session and saving them in individual audio files. We then cut out passages beneath a certain threshold using the tool *Audacity*. Thus, the remaining files implicitly included various verbal social interaction cues that previously were used to analyze co-located multiplayer games [6]. Eventually, the length of each audio file was used as a measure for communication quantity. To assess the number of cooperative interactions, we logged the number of cooperative shots (consecutive shots and thunderstorm clouds). The resulting value represents the amount of cooperation of the team.

3) Control Variables: Since expertise in gaming and VR technology usage may impact the behavior, rating, and performance of players, we determined the player expertise using ten self-formulated items. Each question was required to be rated on a five-point Likert scale. Furthermore, we used the *immersive tendencies questionnaire* (ITQ) to determine the immersive tendency, which was evaluated to positively correlate with spatial presence [21]. To observe potential simulator sickness effects, we used the *simulator sickness questionnaire* (SSQ) [12]. The familiarity between teammates was assessed by self-report on a 5-point Likert scale.

B. Design and Procedure

We used a non-repeated measure between-subject design. Participants played the game in dyads. Each group either played in the remote space condition **(RS)** or in the co-located space condition **(CLS)**. The procedure regarding the questionnaires was the same for both conditions. Before the start of the experiment, participants were welcomed in a shared room and asked to gave their consent. Depending on which condition the group was randomly assigned to, the participants were then separated from each other or remained in the same room. In both conditions, a supervisor was present in each room (see figure 3).

First, participants were asked to report their gaming and VR expertise, and socio-demographic data, and fill out the ITQ, as well as the SSQ to assess whether potential high values of the SSQ after the gaming sessions were due to high values before the game play. After filling out the questionnaires, both players were introduced to the virtual world and played a simple tutorial for about three to five minutes. In the tutorial, they learned how to defeat enemies and how to use the cooperative mechanics of the game. Afterwards, both players played the game for nine minutes. In both conditions, the players communicated via *Discord*, wearing an HTC Vive audio headstrap, to equalize the mode of verbal communication (mediated). PCs were positioned at opposite sides of the play space to minimize the possibility of tangling up the HMDs' cables during gameplay in the CLS condition. After the game ended, participants were asked to fill out the SSQ, CCPIG, and IPQ. Afterwards, the players were asked to rate the perceived communication and whether the presence of the other player (virtual or physical) restricted the perceived freedom of movement and led to deliberate collision avoidance. In conclusion, participants were debriefed and handed certification of participation, which they need for certain university courses. The experiment took about 45 - 60 minutes to complete. The study was reviewed and approved by the university's ethics council.

Fig. 3. In the remote setting, the tracking areas of both rooms were identical, by visualizing the dimensions of one room on the floor of the second room. In both conditions, each HMD requires to be operated on individual PCs. The synchronization of the game is done via a broadband local area network.

C. Participants

Ninety-two participants were recruited and equally distributed to the two conditions - 46 to each group. Exclusion criteria were a history of neurological diseases such as epilepsy. Four participants were excluded from the statistical evaluation since the log files during the gaming session have not been saved correctly. Hence, 88 participants were included in the statistical analysis - 46 in the remote setting and 42 in the co-located setting.

D. Results

1) Sociodemographic Variables: The age of the 88 participants ranges from 18 - 56 ($M = 24.52, SD = 5.26$). 40 participants identified as female, 29 as male, and 19 did not give any information. Considering the general digital gaming behavior, 21% of the participants reported, to never play digital games, 41% reported to play several times a month, and 38% reported to play at least several times a week. The expertise with VR technology can be considered quite low, with 36 participants reporting to have no VR expertise at all and an additional 28 participants reporting to have not used VR more than two times.

2) Simulator Sickness: The SSQ results indicate very low simulator sickness scores for both conditions. The post-game SSQ values for the CLS condition $(M = 4.71, SD = 4.41)$ and RS condition $(M = 3.76, SD = 3.84)$ do not show significant differences between the pre-game SSQ values for the CLS $(M = 7.57, SD = 6.62)$ and RS condition $(M = 6.22, SD = 5.72)$, indicating that the VR game did not induce any simulator sickness.

3) Spatial and Cooperative Social Presence: No significant differences were found for the spatial presence and

TABLE I
IPQ, CCPIG, AND COLLISION AVOIDANCE SCORES

Subscales	CLS M *(SD)*	RS M *(SD)*	*p*
IPQ			
General Presence	4.90 (*0.73*)	4.96 (*1.19*)	.808
Spatial Presence	4.88 (*0.79*)	4.88 (*0.92*)	.988
Involvement	4.18 (*1.03*)	4.40 (*1.28*)	.386
Realism	2.49 (*0.96*)	2.52 (*0.88*)	.996
CCPIG			
Total CCPIG Score	100.67 (*12.71*)	108.96 (*9.97*)	**.001**
Team Involvement	43.45 (*5.66*)	47.05 (*4.77*)	**.002**
Team Cohesion	57.22 (*5.66*)	61.91 (*6.12*)	**.002**
Collision Focus			
Movement Restriction	1.79 (*0.90*)	1.67 (*1.01*)	.587
Collision Avoidance	2.45 (*1.38*)	2.13 (*1.34*)	.271
Attentional Focus	3.12 (*1.09*)	3.22 (*0.99*)	.657

all subscales of the IPQ. One-way ANOVAs revealed significant differences for the experience of the total social presence CCPIG score between the CLS and RS condition $F(1, 86) = 11.69, p = .001, \eta_p^2 = .12$. Furthermore, significant differences were found for the *Team Involvement* subscale $F(1, 86) = 10.41, p = .002, \eta_p^2 = .11$ as well as the *Cohesion* subscale $F(1, 86) = 10.08, p = .002, \eta_p^2 = .11$ between the conditions. The corresponding values can be found in table I. Since we used the cooperative social presence to assess the task awareness, our first hypothesis is confirmed. The scores regarding the questions assessing the freedom of movement and deliberate collision/contact avoidance are surprisingly low (see table I). We have found no significant difference for any question between the two conditions.

4) Communication, Interactions, and Performance: A one-way ANOVA revealed a significant higher qualitative communication score in the RS condition $(M = 21.84, SD = 2.19)$ than in the CLS condition $(M = 20.60, SD = 2.80)$ $F(1, 86) = 5.14, p = 0.26, \eta_p^2 = .056$ and thus confirms our hypothesis *IIa*. No significant differences were found for the quantity of communication. Furthermore, no significant differences were found for the cooperative interactions, though a tendency is observable which indicates a slightly higher summed up value for all cooperative interactions for the RS setting $(M = 394.33, SD = 109.44)$ than for the CLS setting $(M = 363.60, SD = 111.02)$ with $F(1, 86) = 1.71, p = .195$. Hence, we reject our hypotheses *IIb* and *IId*. Since the performance of the players can be assessed using the numbers of killed monsters and books stolen, we calculated two one-way ANOVAs to investigate a potential impact of the setting on the performance. A significant difference was found for the amount of killed monster between the CLS $(M = 107.38, SD = 26.11)$ and RS $(M = 119.78, SD = 26.00)$ condition $F(1, 86) = 4.98, p = .028, \eta_p^2 = .055$. The number of stolen books did not differ between the groups. Since one performance indicator significantly differs between the groups, our hypothesis *IIc* is partly confirmed.

5) Confounding Variables: Since previous gaming and VR expertise, simulator sickness, immersion tendency, and familiarity of the players can influence the gaming experience and thus have a potential impact on our dependent variables, we calculated correlations between potential confounding variables and our dependent variables. We only found correlations between the familiarity of the players and several dependent variables. The familiarity between the player positively correlates with the total CCPIG Score $r(88) = .32, p = .002$, the team involvement $r(88) = .26, p = .015$ and team cohesion subscale $r(88) = .34, p = .001$, as well as with the quality $r(88) = .31, p = .004$ and quantity of communication $r(88) = .40, p < .001$. Hence, this indicates that the familiarity between the player might have impacted the findings of the one-way ANOVAs. Therefore, at first, we investigated whether the reported familiarity values of the players differ between the two conditions. No significant difference was found. Afterwards, multiple analyzes of covariance were conducted to detect differences between the game settings while controlling for player familiarity as covariate. Since only three participants reported familiarity values of 2 and 3, we excluded these cases for the multiple analyzes of covariance. The results of the multiple analyzes of covariance show no deviations from the one-way ANOVA results. This indicates that familiarity does not influence the significant differences between the RS and CLS condition for the experience of social presence, quality of communication, and amount of killed monsters.

V. DISCUSSION

The main results of our experiment reveal significant differences in the experience of cooperative social presence (team cohesion and involvement). Further, we found significant differences in the quality of communication and performance between the CLS and RS conditions. In consequence, we assume that the physical presence or absence of the players had an impact on player experience and behavior in our VR multiplayer game. Based on the assumption that the CCPIG is an adequate operationalization for cooperative task awareness, these results confirm our first hypothesis, that playing together co-located reduces the task awareness. Our second hypothesis is partly confirmed, in that co-located play leads to lower values of behavioral aspects of cooperation based on the shift of player focus.

Referring to [14], one reason for a reduced task awareness could be a shift of focus to collision avoidance. However, we did not find any significant differences between our conditions regarding the perceived freedom of movement and avoidance of physical contact. Thus, we cannot confirm that a focus on collision avoidance did consciously interfere with the focus on task completion. Therefore, we would argue that unconscious processes may explain the constellation of our study results. We assume that our game provided a certain degree of engagement, that prevented players from consciously focusing on aspects that were related to the physical space surrounding them. Thus, we were not able to reveal these processes with the self-report instruments we used. Future work should consider assessing both, conscious (self-report) as well as subconscious measures (clearance distance as in [14]) of player focus to validate this assumption. Furthermore, we deliberately decided that collisions can occur to evaluate which impact collisions and collision avoidance behavior have. Preventing collisions by specific game design choices should be evaluated in future research to explore the role of potential collisions on the game experience and cooperative social presence.

In contrast to [14], we should consider the use of wired HMDs as a potential confounding aspect of our spatial setting and its influence on cooperative social presence. Participants in both conditions often reported the wires of the HMDs had restricted their perceived freedom of movement. Additionally, in the CLS setting, some participants reported they were afraid of the wires tangling up although the cable setup was carefully implemented and did not cause any actual problems during gameplay. However, this could have also caused a shift in player focus that we did not assess systematically.

Although we have found a significant difference in the quality of communication, we did not find a significant difference in the quantity of communication. Thus, we assume that the quality of communication was not based on the amount, but the contents of the communication. This indicates, that though both groups communicated a similar amount of time, the communication was more effective in the RS condition. This would align with the findings on cooperative social presence, in that a higher focus on the cooperative task facilitates effective communication about it. However, since we did not analyze the communication audio files content-wise, we cannot validate this interpretation ultimately. Another potential influencing factor for the reported differences in communication quality is the mediation of verbal communication via Discord in our study. In CLS condition setting, this led to situations, were players heard each other twice (non-mediated and mediated) with a short delay. Although we used the same mode of verbal communication in both settings to ensure comparability, this instance has been remarked by several players and thus, could have undermined the quality of communication.

In line with the previous argumentation, remote players performed significantly better than co-located. Thus, we explain this difference with a higher focus on the cooperation, and more effective communication. Similar to the differences in perceived communication quality, this difference appears not to be based on the number of cooperative attacks, but on their effectiveness. Based on the higher quality of communication, remote players might have coordinated and used cooperative as well as individual attacks more effectively.

Though our results are in line with [14], they are contrary to the results of [1] who also examined a multiplayer VR game with a similar research focus. This contrast can be seen as the results of the VR system, which was used in the studies (cardboard vs. room-scale VR). While cardboard systems seem to equalize potential benefits that result from co-located non-VR multiplayer settings, room-scale VR can shift them to the remote setting. This instance can be explained with regards to the potential physical influence the other player has while sharing the same physical space. For the design of future VR multiplayer, researches should therefore carefully consider which system should be used and which restrictions should be implemented to avoid unwanted side effects.

Future research should use validated methods to analyze the quality of communication. Further, it is interesting to investigate how modern wireless room-scale VR technology impacts the cooperation and to which degree our findings are influenced by the wired setup. Furthermore, in this context, it is interesting to track behavioral data to get a better insight into the player's collision avoidance and movement. This could also shed light on the question to which degree collision avoidance in multiplayer room-scale VR is conscious.

VI. Conclusion

Our study indicates that separating or co-locating two players physically in a multiplayer VR game can have a significant impact on the player experience. In line with our expectations and prior research, co-located play can undermine the experience of cooperative social presence, quality of communication, and performance. Thus, in extension to previous work, our results indicate that unconscious processes due to the physical co-presence of the other player and the technical properties of the setup influence the experience and effectiveness of cooperation. Nevertheless, our results should be interpreted with the discussed limitations in mind. Depending on the specific application domain (e.g., educational games, entertainment games), the objective of VR interaction could either be experience, or performance driven. To ensure better design decisions in such domains, future research should further investigate more facets of player experience and performance in multiplayer VR.

Our work contributes to the understanding of interaction in multiplayer VR and how it affects player experience and behavior and emphasizes the importance to carefully consider which physical spatial relationship between users should be used in future investigations. Since room-scale VR recently became an affordable technology for the consumer and business market, our results inform the growing number of developers and researchers alike that want to create multi-user content purposefully.

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Publication

Title:

Motivating Players to Perform an Optional Strenuous Activity in a Virtual Reality Exergame Using Virtual Performance Augmentation

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Motivating Players to Perform an Optional Strenuous Activity in a Virtual Reality Exergame Using Virtual Performance Augmentation

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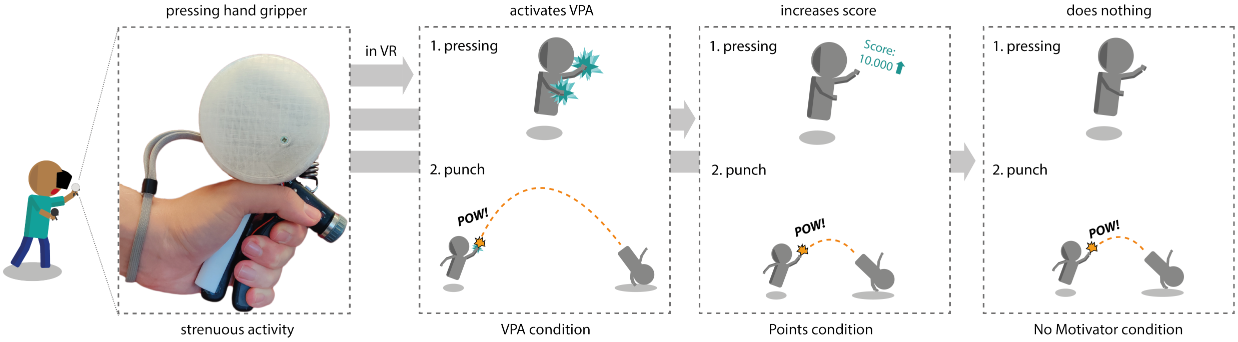

Fig. 1. The novel controller we developed to control our VR exergame is based on a hand gripper that is tracked using an HTC Vive Tracker and can optionally be pressed together while playing the game. To motivate players to press the controller together voluntarily, we have implemented a Virtual Performance Augmentation (VPA) mechanism that exaggerates the visualized strength of the player's stroke when the controller is pressed together. To investigate this approach's motivational impact, we compare the VPA mechanism with a condition in which the squeezing is rewarded with points and a control condition without a motivator.

Research on VR Exergaming is mostly conducted with participants who are not presented a choice whether or not to play the exergame and thus to perform a certain strenuous activity. Whether players would engage in such activity if it were optional and how they could be motivated to do so is mostly neglected. Therefore, we have developed a novel controller and implemented a VR exergame that utilizes Virtual Performance Augmentation (VPA) to motivate players to engage in an optional strenuous activity. The motivational impact of three different conditions (VPA vs. Points vs. No Motivator) was evaluated in a study with 47 participants. Our results suggest that using VPA can significantly increase the time the players engage in the strenuous activity enriched by VPA, while in contrast to our hypotheses, no significant differences for the players' enjoyment and perceived exertion between the conditions were found. We discuss our findings in the context of motivation, exertion, and the resulting implications for further VR exergames research.

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CCS Concepts: • **Human-centered computing** → **Virtual reality**; • **Applied computing** → *Computer games.*

Additional Key Words and Phrases: Virtual Reality; Exergame; Controller; VR; Motivation; Exertion; Voluntarily; Virtual Performance Augmentation; VPA; Game; Digital Game

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1 INTRODUCTION

Digital games"*[...] where the outcome of the game is predominantly determined by physical effort*" [43] are called exertion games or *exergames*. Exergames can be used to support psychological therapy as well as to prevent and counteract obesity and can enhance physical rehabilitation [4, 18, 19, 38]. With the introduction of the new generation of virtual reality (VR) systems like the HTC Vive or the Oculus Rift and the related room-scale paradigm, controlling games using body movements became a central part of digital gaming. At the same time, VR systems have a high degree of immersion through the use of a head-mounted display (HMD), which in the context of VR systems can positively influence the motivational effects of exergames [6, 40, 52, 66]. VR exergames can even further increase the player's motivation compared to non-VR exergames [6, 40] and are thus used for different physical activities to reduce the perceived exertion of the players [2, 40, 67]. In addition, current studies suggest that VR exergames are suitable to support physical rehabilitation due to their high motivational potential [14, 26, 32].

However, most of the works that have investigated motivation in the context of VR exergaming have not given the players a free choice to perform the strenuous activity. Playing and progressing in the game was inseparably connected to the strenuous movement's execution, e.g., [3, 7, 30]. Although high motivation values in different studies could be observed, the task definition in the respective studies stipulated that the participants had to play the respective game version of the VR exergame. This leads to the question of whether the mechanisms evaluated as motivating in VR exergame studies can motivate players to exert themselves voluntarily at all if they were given a choice.

To create a VR exergame that facilitates the execution of an optional strenuous activity, we first developed a novel controller based on a grip strength trainer/gripper with an HTC Vive tracker mounted to it and which is held in each hand while playing. The controllers are equipped with pressure sensors and a single-board microcomputer, which can transfer the pressure the player applies to the controller into a game at runtime. The task of the players is to knock out opponents in a game using their hands. While playing the game, the players can voluntarily press the controller together.

To provide a motivational incentive to press the controllers together, we decided to apply the idea of *Virtual Performance Augmentation* (VPA) from Ioannou et al. [30]. The basic idea of VPA is to represent the virtual abilities of the players exaggeratedly compared to their actual prowess. In VR (exer)games, it has already been shown that the use of VPA can further increase the motivation of the players [20, 30, 60]. Therefore, in our VR exergame, the visualized strength of the player's strikes is exaggerated when the player presses the controllers together.

In a study with 47 participants, we investigated whether VPA is suitable as a motivator to train with the controller voluntarily. We compared the VPA condition against a condition with points as a motivator and against a control condition without a motivator. Our results show that using VPA can significantly increase the period the controllers were pressed together while maintaining a high intrinsic motivation. At the same time, the perceived exertion does not differ between the conditions. We discuss our findings in the context of the interplay of motivation, (optional) exertion, and how virtual performance augmentation can serve as a motivator for future VR exergames.

2 VR EXERGAMES

In the context of exergames, VR systems and the associated high level of immersion and presence can positively affect the player. Analogous to Slater [55] we define immersion as an objective characteristic of a technology that describes the extent of its user's technical integration into a virtual environment. The user's experience of presence which is often described as the feeling of "*being there*" [27] or simply as *presence* can be seen as a direct consequence of immersion [56]. Even though we understand immersion here only as an objectively classifiable property of a system, particularly in gameplay research, immersion is defined in a far more detailed way, such as in the SCI-model [15]. Besides sensory immersion, which most closely matches Slater's technical definition and is particularly high when stimuli from the real world are overlaid by virtual ones, the SCI model also considers challenge-based and imaginative immersion important dimensions of immersion. Thus, a variety of immersion dimensions can influence the game experience of players. However, in the following, we focus on sensory immersion or immersion in a technical sense, as we want to highlight the influence of VR systems in the context of exergames. HMDs, in particular, offer a high degree of immersion which, in the context of exergames, can even create more presence than VR cave systems [50]. Thus, in the following, we refer to the term VR exergames as exergames including an HMD.

In the context of exergaming, VR is often used to distract from repetitive movements such as cycling or rowing. The results of different works suggest that for this use case, VR exergames lead to more enjoyment, self-efficacy, physical effort, and a lower perceived exertion compared to non-VR exergames [40] and to the actual exercise [40, 67]. Even for high-intensity training [16] and experienced athletes [2] VR exergames show advantages regarding motivation and perceived exertion compared to the non-gamified exercise. Due to the positive effects VR has as a distractor, it gained popularity over the last years with a great variety of works focusing on specific attributes that can further enhance these types of VR exergames [3, 22, 23, 29, 34–36, 42]. However, besides using VR as a distractor for repetitive exercises, modern VR systems can facilitate a much greater variety of movements using accurate (body) tracking. Thus, the design of the gameplay design is not limited by the training device. This allows for a much greater variety of controlling the exergames, which requires the players to pay more attention to the movements since they are less predictable and therefore cannot be performed unconsciously.

In their work, Finkelstein et al. [17] developed the immersive exergame *Astrojumper* that is played inside a three-sided stereoscopic cave system. The authors observed that high levels of motivation were accompanied by high levels of perceived exertion. Further, Born et al. [6] systematically investigated the role of the output device, perspective, and tracking fidelity on the player's presence, motivation, and exertion using their immersive VR game *Fit the Shape*. Their results suggest that output device and perspective have the most significant impact on the player's motivation and presence. However, though the player's motivation was significantly increased, their perceived exertion did not differ between the conditions.

The results of the studies suggest that this area of VR exergames also offers great motivational potential and that the distraction from a strenuous activity does not have to be the primary focus since high motivation values can be achieved despite high perceived exertion. Also this VR exergame research domain has been increasingly focused on in recent years under different aspects [7, 62–65].

Although VR-HMD technology can thus be beneficial for exergaming, the use of an HMD and VR technology can also lead to unwanted effects, such as simulator sickness [57], the weight and heat of the HMD being perceived as disruptive [3] and sweat accumulating under the glasses [53], which can be perceived as unhygienic. However, despite these problems, the player experience can already be significantly enhanced in various aspects with current VR technology, as presented above. For this reason, and because HMDs are constantly improved, using VR for exergames is a promising approach.

2.1 VR Exergames and Motivation

The majority of studies on VR exergaming has focused on the intrinsic motivation of players since engaging in and enjoying a specific activity is based on being intrinsically motivated [49]. According to the self-determination theory of Ryan and Deci [47], intrinsic motivation for a particular behavior depends on the extent to which the three basic needs for competence, autonomy, and relatedness can be satisfied. However, in most of the mentioned studies on (VR) exergaming, the participants did not have the autonomy to decide to perform the exerting activity which was used to interact with the game since controlling the game was inseparable from the strenuous activity and the task of the respective study stipulated to play the game. This raises the question of what would result from decoupling the exerting activity from controlling the game and thus giving the player the choice to perform an exerting activity voluntarily.

On the one hand, the players' autonomy and thus a potential influence for their intrinsic motivation could be increased. Also, the optionality of executing an exerting activity allows drawing a much more accurate conclusion about the players' actual motivation and the true motivating nature of the mechanism that can be implemented to reward the players when they perform an exerting activity. This could be particularly useful for exergames that aim at high levels of exertion to counteract the problem, that exergames often fail to increase the level of energy expenditure and may not contribute to the recommended daily amount of exercise [21, 45]. On the other hand, however, giving players the free choice leads to the question if players would engage in an optional strenuous activity at all. Given that physical exertion can negatively affect the player's motivation [13, 61], this approach suggests an optional strenuous activity will not be performed without a suitable motivator. Thus, the question arises, which motivator could be used to incentivize the players to perform an optional strenuous activity. However, it must be considered that potential motivators are external incentives, which are thus opposed to purely intrinsically motivated actions. However, according to the Organismic Integration Theory (OIT) [11] the better persons can align external motivations with their own sense of self, the more strongly the extrinsic motivator will be internalized, and the more autonomous and thus motivated the person will be when engaging in the incentivized behavior. Thus, it is essential to use incentives, which have a meaningful character for the player to support voluntary engagement in an optional strenuous activity.

Ketcheson et al. [33] have presented a first approach to motivate players' to perform optional strenuous activities. In their non-VR exergame, players received power-ups if they increased their heart rate to a predefined value using a recumbent bicycle connected to the game. The players' exertion could thus be increased significantly. Unfortunately, the authors did not systematically record or evaluate the players' motivation. Besides, the players had to train with the recumbent bicycle to control the game independently of the power-ups. Another approach was presented by Davis et al. [10]. In their application, the game's visual appearance depended on the player's heart rate and improved when the heart rate increased. However, the authors did not evaluate their concept. Nevertheless, these works give a good insight into the fact that game mechanics could be used as a motivator to voluntarily engage in a strenuous activity if they offer a valuable benefit to the gaming experience. If this idea is transferred to a (room-scale) VR exergame, which is not controlled by a rowing machine or an exercycle, the question arises, which game mechanic can be used as a motivator to engage in an optional strenuous activity.

2.2 Virtual Performance Augmentation

One novel approach to increase the players' motivation in (VR) exergames is the adaptation or enhancement of the capabilities of the player's avatar. Current VR systems allow a precise transfer of body movements into virtual worlds and avatars. According to Ioannou et al. [30], if the virtual effect of the body interaction is then exaggerated, a sense of empowerment and thus an increase in perceived competence and motivation can occur. This approach was explored in several studies on non-VR [24, 37] and VR applications [20, 30, 60] and is either called mixed reality empowerment [25], expressive amplification of interaction [25], or virtual performance augmentation (VPA) [30] which is the term we use in the following. The influence of VPA on player motivation was systematically investigated for VR in particular. In their work, Granqvist et al. [20] have shown that when virtual kicks are displayed exaggeratedly compared to real body movements, performance and motivation-relevant variables of the players can be increased. Following works further observed that virtually exaggerated running speeds [30] and jumping heights [30, 60] can significantly increase the players' motivation. Based on these results, the question arises whether VPA can be used and implemented as a motivator to support voluntary engagement in strenuous activity in a VR exergame.

Therefore, we have developed a VR exergame, which includes an entirely optional VPA feature that does not impact the basic game principle and goal. Although the question of whether VPA can support voluntary engagement in a strenuous activity does not necessarily require VR technology, we deliberately chose to use an HMD VR system. On the one hand, player motivation and presence in exergames can be significantly increased through the use of an HMD [6, 40]. On the other hand, following the argumentation of Ioannou et al. [30], VR could strengthen the identification between the player and the avatar to induce a feeling of embodiment which can contribute to generating a convincing VPA experience. In our VR exergame, the player can engage in a strenuous activity while playing to improve the virtual representation of their skills. Similar to [6, 7, 17], we do not use VR as a distractor from a monotonous strenuous exercise but generate the necessary movements from the gameplay, which allows us to create more diverse interactions. To investigate the effect of VPA as a motivator, we have implemented three different versions that differ in the type of motivator used. In a subsequent study, we investigate the effect of the motivators on the player's motivation to engage in an exerting voluntary activity. However, the comparison between the classical paradigm of exergames where players have to perform an exerting task to progress in the game and voluntary exertion is not part of this work since we, first of all, evaluate whether players can be motivated to perform a voluntary strenuous activity at all.

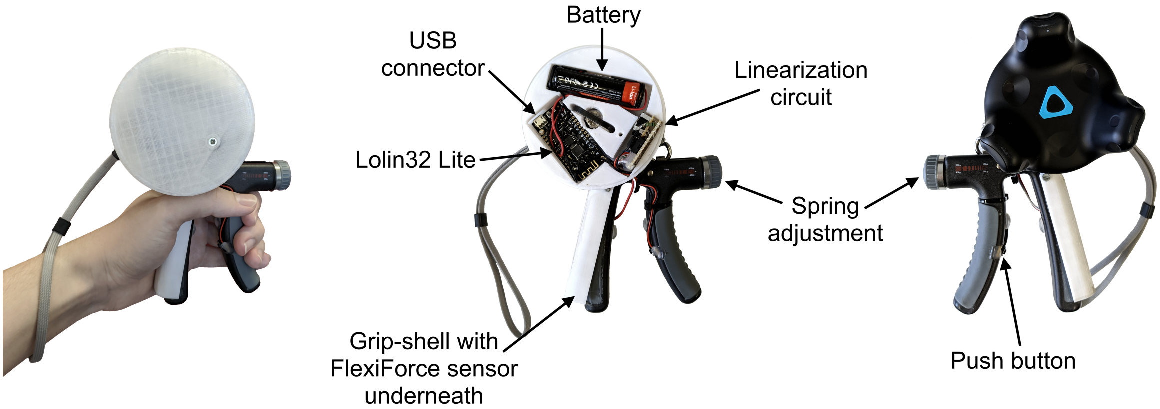

Fig. 2. Side elevation views of the Grip It controller. In the illustration in the middle, where the cover of the case is removed, the most important components are labeled.

3 GRIP CONTROLLER

To allow the player to interact with the game, we have built a new type of controller with two main features. The first is to track the player's hand movements using an HTC Vive tracker and transfer them onto a virtual representation. The second is to measure the force the player is applying while pressing the controller together and transmitting the value to the game. We chose to press a hand trainer as a strenuous interaction since this interaction can take place in parallel with playing in VR without interfering with the primary interaction. Furthermore, pressing a hand trainer is intuitively understandable and something that most players can do regardless of their athleticism or physical condition. In addition, pressing the controller produces an immediate exertion with a quickly perceivable discomfort.

The controller is based on a hand gripper where the force required to press it together completely can be adjusted between 20kg and 40kg. To track its movements, we mounted an HTC Vive tracker on the gripper. To capture the force the player exerts on the hand gripper, we used a *FlexiForce* pressure sensor. This sensor is located between the palm rest of the hand gripper and a 3D-printed grip shell placed on top. The shell is attached at the top of the palm rest with a single screw acting as a pivot joint to concentrate as much of the force exerted on the palm rest on the pressure sensor as possible. On the inside of the front grip, we installed a push-button to detect whether the gripper is fully closed. Upon pressing the button, the current force is set as a maximum value candidate. Bluetooth Low Energy is used to transfer the sensor readings to the game. A *Wemos Lolin32 Lite* development board is responsible for reading, processing, and sending the sensor data. An operational amplifier-based linearization circuit was installed between the development board and the sensor to obtain linear measurement values from the sensor. It is based on the non-inverting reference design by the FlexiForce manufacturer Tekscan since it has good linearity compared to a simple voltage divider and, unlike the inverting design, does not require an additional power source. To safely install the electronics, a case was modeled with *FreeCAD* and printed using *Ultimaker Cura slicing software* and an *AnyCubic Mega S 3d*. The *ESP32 Gamepad* and *Espressif Arduino-ESP32* program libraries were used to establish a Bluetooth connection with the computer running the game and to transmit the sensor data as a standard HID game controller input. The controller can be seen in Figure 2. We created two identical controllers to integrate both hands of the player into

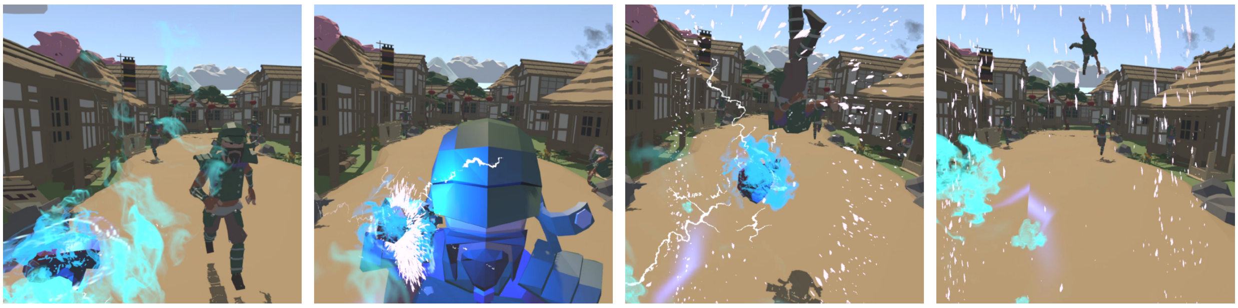

Fig. 3. The player has reached the highest VPA level. The opponent running towards the player is hit and knocked away over a long distance.

the game.

4 GRIP IT

To investigate the characteristic of VPA as a motivator to engage in a strenuous activity, we have developed the VR exergame *Grip It* using the game engine *Unity*. The setting takes the player to a village, which is visually similar to feudal Japan. As shown in Figure 3 the player's task is to knock out approaching enemies to defend the village. There are three different types of enemies, which differ in their attacks and hits they can withstand. The enemies automatically run towards the players and always attack them from the front. Hence, we avoid the player's necessity to turn around frequently and thus a potential simulator sickness influence. The game is played from a first-person perspective, where the in-game player representation is limited to a pair of hands. The player can only defeat the opponents in the game by hitting their heads. This limitation is deliberately chosen to eliminate the problem of accidentally hitting wrong hitboxes on the opponent, and thus the punch not working as expected. To defeat an opponent, it is also necessary for the player's hands to be moving at a specified minimum speed upon impact, which is similar to the speed of a real-life punch. Thus, we wanted to ensure that the motor-sensory action of punching and the visual feedback correlate in the virtual world and to prevent the player from defeating enemies by barely touching them. Each game round lasts around five minutes, depending on how fast the player defeats the enemies. The number of enemies to defeat is identical for each round and version of the game. In total, there are three different stages in the game where the player has to fight back the opponents. After one stage is completed, the player is automatically teleported to the next. The different stages have been implemented to offer the player visual variety within the game world. The stages do not influence the basic game concept. Each opponent attacks the player for 15 - 20 seconds before storming into the village. The fewer enemies the player defeats, the more parts of the village are set on fire and the larger the resulting inferno is, which only acts as motivational visualization. The opponents' height is adjusted to the players' height at the beginning of the game to ensure that the punching movements are similar for each player.

The basic gameplay is the same in all versions. However, the effects of pressing the controllers together are different so that the impact of the respective gameplay effects can be investigated systematically in a subsequent study. In total, we developed three different versions. As a strenuous interaction, we decided that the controller must be pressed together and then held in this position. Thus, we wanted to ensure that a simple exerting interaction is chosen that can be performed while playing.

In the VPA version, the visual representation of the player's punches is exaggerated. In contrast to work such as that of Ioannou et al. [30], in our work, the visual representation of the punches is not automatically augmented. A real-life punch does not automatically lead to an exaggerated virtual punch. Instead, the players can control the degree of virtual performance augmentation by pressing the controllers. The VPA mechanism is supposed to incentivize the player by its motivating character to press the controller and thus engage in the strenuous activity. If the controllers are pressed together, the internal VPA value increases, which reaches its maximum after 10 seconds. If the controllers are released, the value is reduced and reaches 0 after 3 seconds. By reducing the VPA value much more quickly than increasing it, we aim at providing the players an additional incentive not to release their grip during the game or between punches. The value increases when the force exerted on the controller exceeds 75% of the force necessary to press the controller together completely. In the VPA condition, we use three visual components to create the illusion of exaggerated strength: idle effects, punch effects, and ragdoll behavior of the defeated opponents. The idle effects are visual effects that are displayed around the player's virtual hands. For this, we use blue flames, lights, and lightning bolts. If the VPA value exceeds the limit for the next level, the associated idle effect is activated in addition to those of the lower levels. Also, the player's hands emit light that increases in intensity in proportion to the VPA value. The punch effects consist of clouds of smoke and spark explosions. If opponents are knocked out, they leave their current animation and go into a ragdoll mode, where their limbs can move freely within the degrees of freedom of their joints. This is supposed to suggest an unconscious body without muscle tension in an exaggerated way. The higher the player's VPA value, the greater the force multiplier applied to the force hurling the opponent in the strike's direction after knocking them out. Hence, with a maximum VPA value, the enemies fly several hundred meters away, whereas, with a VPA value of 0, they only fall over on the spot. While the trajectory and particle effects serve as the most vital indicators of exaggerated strength, the idle effects are designed to remind the players that they have increased strength even between punches. We have deliberately decided that the changes in the game using VPA are only visual and do not provide any actual game benefit. The player's VPA level does not influence how fast an enemy is defeated or how large the inferno is. The inferno is influenced solely by the number of defeated opponents. The period in which an enemy exists depends only on when that enemy is defeated regardless of the VPA level. Thus, we decouple the effects of pressing the controllers together from progressing in the game. In addition to representing increased strength, the VPA mechanism's visual effects serve as visual embellishments to increase the game's juiciness. Based on the results of Hicks et al. [28] juicy game design can increase a game's visual appeal but not objective player performance. Thus, we assume that the comparability regarding the player performance is not affected by the visual effects of the VPA condition.

The second version we developed uses points as a motivator for pressing the controller together. Like the VPA mechanism, points are an external motivator, but in the context of games, they can serve various functions and can be used as an incentive for a particular behavior. Points can be used to present direct feedback, a reward, or a challenge to the player, depending on the context [46]. In our implemented version, the player's current points are displayed above the left wrist. The points increase for each opponent the player defeats. However, the player can also increase these points by pressing the controller together. Next to the overall score, a second value shows the current score the player has gained by pressing the controller. Thus, the points in our implementation serve as direct feedback and a reward for pressing the controller together and are thus a mechanism for increasing the player's competence, which is directly related to the enjoyment of the game [48].

Fig. 4. Representation of the enemies' trajectories at three different VPA levels. At the lowest VPA level, the (cyan) opponent falls to the ground on the spot. At a medium VPA level, the (yellow) opponent flies several meters away. At the largest VPA level, the (red) opponent is thrown away over a long distance. The flight curves are adapted for this illustration so that they can be displayed in one Figure. The actual trajectories of the enemies are even more exaggerated.

With the points version, we thus have a second version with a motivating mechanism. Hence, with the points version, we can compare one of the most established incentives in digital games with our developed VPA mechanism. The values for activating the point function are identical to those of the VPA condition. In this version, the force multiplier applied to the player's punches and the visual effects around the virtual hands are fixed and correspond to 50% of the VPA maximum value.

The third version serves as a control condition. Also in this version, the players can press the controller together, but this does not affect the gameplay. Since there is no explicit incentive resulting from the gameplay to press the controller in this condition, we refer to this condition as the *No Motivator* condition in the following. Implicit motivation resulting from the nature of the controller or curiosity of the players can, however, represent an additional motivator in all groups. The term *No Motivator* here only describes the lack of incentive resulting from gameplay in contrast to the other conditions. The force multiplier and the visual effects are equivalent to the points version. The three resulting groups and the corresponding names of the conditions are shown in Figure 1.

5 EVALUATION

Our evaluation's central question is whether players can be motivated to voluntarily engage in a strenuous activity using VPA as an incentive. Thus, we investigated how the different implemented conditions affect the participants' motivation, presence, perceived exertion, and duration of pressing the controller together.

5.1 Method

We recorded the length of time each controller was pressed together during the playing time. We then added up the values for both controllers to get one final value. Although the playing time is designed for five minutes, there can be short individual variations per player. To take this into account, we have divided the final value of the sum of both controllers by two and then by the player's individual playing time. The resulting value represents the proportion of the pressed time to the total playing time.

To assess the perceived exertion, we used the Borg Scale [5]. The scale ranges from 6-20 (none - very, very hard). Although the scale is often used in the area of cardiovascular strain and fatigue, the Borg scale can also be used for short short-term exercise and muscular training [5]. This can also be seen from the official instruction of the scale, which instructs the participants to rate their perception of exertion, which "[...] is mainly felt as strain and fatigue in [their] muscles and as breathlessness or aches in the chest" [5]. We have further decided against recording the participants' heart rate since we assume that the primary punching interaction in the game has the most significant influence on the heart rate and that pressing the controller only has a minor influence. Making a statement about the relationship between actual grip exertion and perceived exertion would thus not be possible. This could only be done by continuously recording the actual grip force, which was not possible with our controller. Nevertheless, by recording the period in which the controller was pressed together, we have an indicator of objective exertion since the necessary force to press the controller together was adapted to the individual grip strength. To further assess whether our setup distracted the players' attention, we measured the participants' dissociation and association. Congruent with the research of Mestre et al. [41] dissociation is defined by a focus on external stimuli and distance to internal body stimuli, whereas a focus on internal body stimuli defines association. The attentional focus was rated on a scale from 0 (dissociation) to 10 (association).

The player's motivation was measured using the Intrinsic Motivation Inventory (IMI). The inventory consists of six subscales of which the *Interest/Enjoyment* subscale directly measures intrinsic motivation is thus considered the most significant one [12]. We thus focus on the *Interest/Enjoyment* subscale in our hypotheses in the context of the player's motivation. However, we also assess the remaining subscales (*Perceived Competence, Effort/Importance, Pressure/Tension, Perceived Choice, Value/Usefulness)* to consider a potentially significant difference in intrinsic motivation in the overall picture of the IMI. The scale of each subscale ranges from 1 - 7.

We further measured the experience of presence using the *IGroup Presence Questionnaire* (IPQ) [51] which we use as a quality criterion for the immersive experience. Furthermore, presence and motivation are closely linked in the context of VR exergaming [6]. Therefore the experience of presence should be included as a control variable. The IPQ comprises the four subscales *General Presence, Spatial Presence, Involvement* and *Experienced Realism*. The scale of each subscale ranges from 0 - 6.

Since the players' physical activity level can moderate the perceived exertion and assessment of the exergame, we used the International Physical Activity Questionnaire (IPAQ) [9] to assess the physical activity level of the participants. There are two forms of output, a total value representing the weekly amount of energy expenditure carrying out physical activity and a categorization of the participant's activity level (low, moderate, high activity). Furthermore, we used the Simulator Sickness Questionnaire (SSQ) [31] to assess if our setup causes simulator sickness and if high SSQ values have a negative effect on the rating of the player experience. The resulting SSQ score can be between 0 and 235.62. Also, we asked the participants in all conditions in an optional question about their motivation to interact with the gripper while playing to draw a more precise conclusion about individual motivation.

5.2 Design and Procedure

The study was conducted in a between-subject design. Thus, each participant played only one of the three versions of the game. We deliberately chose not to use a within-subject design to prevent potential subject fatigue, exhaustion, and boredom. The subjects were randomly assigned to one of the conditions. The same dependent variables were recorded in each condition. To not prime the subjects and avoid that only people with a high athletic motivation participated in the study, the study was not framed as an exergame study but as a VR game study in which a new controller had to be evaluated.

After a brief introduction to the study at the beginning of the study, the subjects gave their consent to participate. Subsequently, the participants answered questionnaires on demography, previous experience with exergames and VR, and filled out the IPAQ. Also, the subjects had to fill out the SSQ before playing the game to check whether potential high SSQ values after the game were due to high SSQ values before the VR experience.

After filling out the SSQ, the gameplay phase started. First, the controller was introduced. We wanted to adjust the controller's spring strength to the player's individual grip strength to create a similarly strenuous activity for everyone. Unfortunately, the pressure sensors we used were not calibrated by the manufacturer, and we could not make an exact calibration using a calibrated hand dynamometer that would have allowed us to measure the exact maximum grip force. Furthermore, even a precise measurement of the maximum grip force is not a good predictor for grip endurance, representing the strenuous activity in our game since grip endurance and maximum grip strength are unrelated properties [44]. We, therefore, searched for a quick method to approximate the individual grip endurance strength. Thus, we tested several methods with members of our institute. The resulting method instructs the players to place the index and middle finger on one grip and the same hand's thumb on the other grip. The players are then to adjust the spring's strength so that they can barely compress the controller with this unique grip. The individual controller resistance resulting from the three-finger grip calibration allows the player to press the controller together with the entire hand easily. However, the controller could not be pressed by any pre-tested person over the entire game period and caused significant discomfort after only about 40 - 60 seconds. In the study, the procedure was performed separately for both controllers. Afterward, the participants put on the wireless HTC Vive and received the adjusted controller for each hand.

The player was positioned in the middle of the playing area, which was 3m * 2m in size. The game was introduced with a tutorial in which the participants learned how to fight off the different kinds of opponents. There was an extra section in the VPA condition in the tutorial, which explained the impact and the visual effects of the virtual performance augmentation and let the player test it. In addition, the connection between pressing the controller and the impact on the punching effects was illustrated and could be tested with several test enemies. In the Points condition, there was a reference to the scoreboard attached to the hand, and we explained that the points increased as long as the controllers are pressed together. In the condition without a motivator, it was additionally explained that the controller did not influence the gameplay, but the players could train their grip strength with the controller while playing.

After the players finished the tutorial, the game was started. Each game session lasted around 5 minutes, depending on how fast the players defeated the opponents. After the game, the participants completed the IMI, IPQ, Borg, attentional focus questionnaire, and SSQ. Subsequently, the participants were informed about the study and, if desired, were given a trial hour, which has to be collected in various study programs at our university. The ethics committee of our university approved the experiment.

As the study took place during the corona pandemic, a special corona concept was developed and accepted by our university. All devices were thoroughly disinfected after each use, and the distance between the investigator and the participant was always greater than 1.5 meters. The investigator wore a face mask at all times, while the participants were allowed to take the mask off during the study. In addition to disinfection, disposable covers were used for the HMD, which were changed for each participant.

5.3 Hypotheses

Following the argumentation of Ioannou et al. [30], we assume that the player's augmented performance leads to a sense of empowerment and thus has a more meaningful impact and can be better aligned with the player's sense of self than receiving points. Therefore, we assume that the VPA condition is a better motivator to voluntarily engage in a strenuous activity than the Points condition. Thus, we hypothesize that:

I *The period in which the controllers are pressed together is significantly higher in the VPA condition than in the Points condition and in the condition without a motivator.*

Furthermore, we assume that deliberately engaging in a greater exertion also leads to a higher perceived exertion. We therefore further hypothesize that:

II *The perceived exertion in the VPA condition will be rated higher than in the Points and No Motivator condition.*

We further assume that the VPA mechanic can incentivize the player to press the controller for a significantly longer period since the VPA mechanic can be better aligned with the player's sense of self and thus internalized than the other two conditions. Hence, the players will feel more autonomous and thus are more motivated to engage in the incentivized behavior, which we assume is also reflected in the players' intrinsic motivation. We, therefore, hypothesize that:

III *The players' interest/enjoyment is significantly higher in the VPA condition than in the Points condition and in the condition without a motivator.*

5.4 Results

Because the study took place during the Covid-19 pandemic, we were only able to survey 47 participants. However, we expected a lot more. The resulting test power may therefore be reduced. The interpretation of all results reported in the following sections should take this into account. 22 female and 25 male participants were included in the analysis. 15 participants were assigned to the Points condition and 16 each to the other two conditions.

The age ranges from $20 - 66$ years ($M = 27.34, SD = 10.09$). 76.6% of the participants reported having played an exergame at least once. 48.9% of the participants had no or just a little experience with VR systems, while the remaining 51.1% had at least 5 experiences with VR systems. The IPAQ evaluation showed that the physical activity level of 6 participants can be rated as low, 16 as moderate, and 25 as high.

We calculated one-way ANOVAs and used Tukey-HSD post-hoc tests for the following group comparisons if there was a significant difference. We have used Eta-squared (η^2) as the effect size measure. According to Cohen [8] the values $\eta^2 = 0.01$, 0.06, and 0.14 correspond to small, medium, and large effect sizes. Variance homogeneity according to the Levene test was given for all dependent variables. The normal distribution was checked using the Shapiro-Wilk test as well as Q-Q plots. If no normal distribution was given, a robust one-way ANOVA was performed using the *WRS2* package for R [39] with a trimming of 20% and a bootstrap number of 1000. According to Mair and Wilcox [39] the values of the robust ANOVA's effect size $\xi = 0.10$, 0.30, and 0.50 correspond to small, medium, and large effect sizes. As post-hoc test for the robust ANOVA, we used the TPB20 post-hoc test according to [58, 59]. The descriptive values for the dependent variables and the results for the ANOVAs are shown in table 1. The post-hoc tests are shown in the following subsections.

Table 1. Overview of the mean values, standard deviations, and Cronbach's alpha of the dependent variables and group comparisons based on one-way and robust ANOVAs

Condition Subscales	**No Motivator** M *(SD)*	**Points** M *(SD)*	**VPA** M *(SD)*	$F(2,44)/F_t$	p	η^2/ξ	α
Total Time Pressed							
Total Time Pressed in s[a]	135.5 (*108.1*)	160.7 (*95.3*)	268.4 (*109.1*)	3.53	**.046**	.51	–[c]
Proportion of Playtime in%[a]	24.1 (*18.8*)	31.4 (*21.2*)	45.54 (*18.7*)	3.53	**.049**	.50	–[c]
Playtime in s[a]	282.1 (*13.5*)	291.1 (*20.7*)	295.1 (*21.7*)	1.39	.280	.30	–[c]
Exertion							
Borg[a]	12.86 (*1.93*)	13.00 (*1.56*)	13.44 (*2.07*)	0.33	.731	.16	–[c]
Attentional Focus							
Diss-&Association[a]	7.50 (*2.19*)	8.00 (*1.96*)	7.81 (*2.34*)	0.64	.524	.25	–[c]
IMI							
Interest/Enjoyment[a]	6.03 (*0.97*)	6.13 (*0.96*)	6.10 (*0.77*)	0.64	.524	.25	.88
Perceived Competence[b]	4.96 (*0.97*)	5.07 (*0.83*)	4.64 (*0.94*)	0.94	.399	.04	.77
Effort/Importance[b]	5.99 (*0.81*)	5.80 (*0.63*)	5.60 (*0.81*)	1.05	.358	.05	.54
Pressure/Tension[b]	4.20 (*1.19*)	3.56 (*1.20*)	4.19 (*0.98*)	1.62	.210	.07	.64
Perceived Choice[b]	3.97 (*0.93*)	5.15 (*0.74*)	4.37 (*1.00*)	5.55	**.003**	.24	.63
Value/Usefulness[b]	5.59 (*0.82*)	5.15 (*1.19*)	5.29 (*0.86*)	0.84	.438	.04	.87
IPQ							
General Presence[a]	4.81 (*1.28*)	4.53 (*1.13*)	4.50 (*1.27*)	0.61	.56	.19	–[c]
Spatial Presence[a]	4.59 (*1.18*)	4.71 (*0.88*)	4.76 (*1.16*)	0.78	.463	.19	.75
Involvement[b]	3.77 (*1.36*)	3.89 (*1.31*)	3.86 (*1.14*)	0.37	.938	< .01	.76
Experienced Realism[a]	2.09 (*1.01*)	1.50 (*0.81*)	2.67 (*1.25*)	6.09	**.006**	.56	.65

[a] Here a robust ANOVA was calculated - F_t & ξ
[b] Here a one-way ANOVA was calculated - $F(2,44)$ & η^2
[c] Since these scales consist of less than three items, Cronbach's alpha could not be calculated

5.4.1 Duration of pressing the controllers together. A robust ANOVA revealed a significant difference for the percentage of the playtime in which the controllers were pressed together between the three conditions. A following post-hoc test revealed a significantly longer pressing time for the *VPA* condition in contrast to the *No Motivator* condition $p < .001$ and in contrast to the *Points* condition $p = .046$.

5.4.2 Motivation. For the IMI only for the Perceived Choice subscale a significant difference was found using an ANOVA. For this subscale, the *Points* condition shows significantly higher values than the *VPA* condition ($p = .002$) and the *No Motivator* condition ($p = .049$). No other significant differences were found.

5.4.3 Perceived exertion and attentional focus. Surprisingly, a robust ANOVA did not reveal a significant difference for the Borg values between the conditions. The perceived exertion can be described as somewhat hard in all conditions. Further, also for the attentional focus, a robust ANOVA did not reveal a significant difference between the conditions. Since all conditions' values are greater than 5, the participants reported a more associative body focus.

5.4.4 Presence. A robust ANOVA only revealed a significant difference for the *Experienced Realism* subscale. The following post-hoc test revealed significantly higher values for the *VPA* condition in contrast to the *Points* condition ($p = .010$). No other significant differences were found.

5.4.5 Simulator sickness and physical activity. The SSQ values before ($M = 25.94, SD = 25.28$) and after the gameplay ($M = 23.40, SD = 21.12$) are very low and therefore do not give a reason to assume that the game triggered simulator sickness. Furthermore, we calculated correlations to investigate whether the players' physical activity level influences the controllers' pressing period and player experience. The resulting IPAQ value does not correlate with the total time the controllers were pressed together $r = -.12, p = .414$. However, the IPAQ value positively correlates with the *Interest/Enjoyment* subscale of the IMI $r = .38, p = .009$.

5.4.6 Reported Motivation. To compare the main motives, as shown in Figure 5, we first analyzed the participants' responses and then assigned them to four main categories. We observed that the motive *Increase strength* is most dominant in the VPA condition, but interestingly also plays a central role in the other two conditions, although the virtual strength could not be influenced there. Furthermore, the motive *Authenticity* has a similarly high impact in all groups and represents the fact that hitting with a fist seems more authentic, and the controller was hence pressed together. As expected, the motive of receiving points was almost exclusively mentioned in the Points condition but was also mentioned once in the VPA condition, although no points were displayed there. The motive of voluntary physical engagement as the main reason for pressing the controller together was mentioned only four times.

6 DISCUSSION

The idea of our work was to investigate whether players could be motivated to voluntarily engage in an optional strenuous activity using virtual performance augmentation. Our results show that the three conditions differ significantly in their proportion of playtime in which the controllers were pressed together. The controller was pressed significantly longer in the VPA condition than in both other conditions. Thus, we confirm our first hypothesis. VPA seems to be so motivating for the players that they voluntarily went for a greater exertion, although the augmentation of strength did not influence the gameplay or progressing in the game besides the visual effects. Thus, beyond the observed self-reported high motivation values VPA could elicit [20, 30, 60] our results suggest that VPA can actively motivate players to perform a strenuous movement voluntarily. This

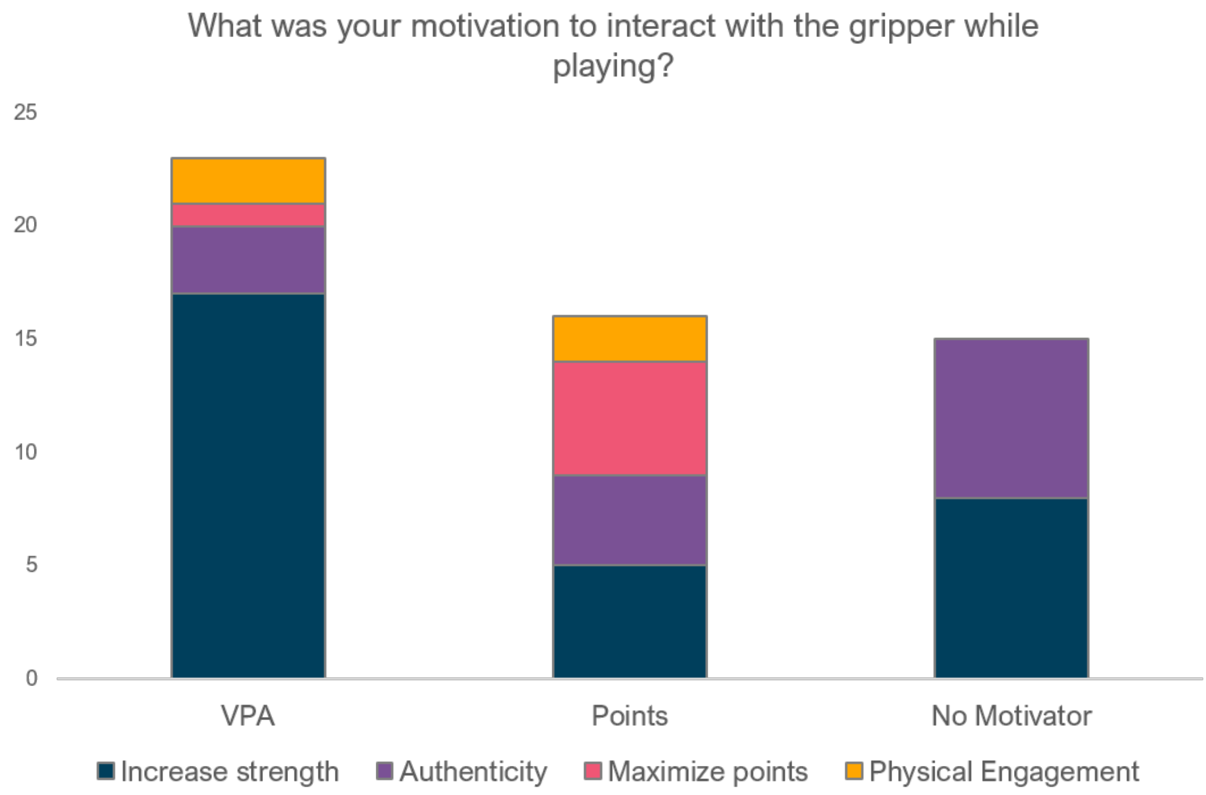

Fig. 5. This bar chart shows the distribution of players' motives for pressing the controller together divided into the three study conditions.

result is particularly interesting for following works, which like Ketcheson et al. [33] and Born et al. [7] try to increase the players' exertion without reducing their motivation.

Surprisingly, we observed no significant difference for the interest/enjoyment of the players between the conditions. Thus, we reject our third hypothesis. This finding is interesting since, on the one hand, VPA has acted as a motivator with regards to the time in which the controllers were pressed together but, on the other hand, could not lead to observable differences in the self-reported interest/enjoyment of the players. Especially when compared to the work of Ioannou et al. [30], which served as the basis for our work and reported higher motivation scores among players in the VPA condition, the non-observable difference in our study seems unusual. Thus, we assume that the main game in our work seems to be the most influential factor for the interest/enjoyment, which, as in the condition without a motivator, can already achieve very high interest/enjoyment scores without the VPA mechanism. This tendency can also be observed for the other subscales of the IMI, all of which, except for the perceived choice subscale, show no difference between the conditions. Interestingly, for the perceived choice subscale, significantly higher values for the Points condition than both other conditions can be observed. The freedom of choice to press the controllers together was identical in all conditions. Somehow, receiving points moderated this perception. However, since the Cronbach's alpha of this subscale is relatively low, this finding has to be interpreted with care and with the low reliability in mind.

Furthermore, our results observed no significant difference for the perceived exertion between the groups. Thus, we have to reject our second hypothesis. Though the players in the VPA condition pressed the controllers together for a significantly longer period and thus had to apply more physical effort, no significant difference for the perceived exertion could be observed. Regarding the VR exergame of Born et al. [7] who deliberately increased the exertion and observed a corresponding increase in the perceived exertion, the question arises, why this effect could not be observed in our study. In our study, there were two factors influencing exertion: the punching interaction and pressing the controller together. Even though we explicitly asked about muscle fatigue with the Borg scale, the rating of perceived exertion could primarily be based on the punching interaction with the game, which was identical in all conditions. A further assumption could be that the interaction with the controller was not perceived as strenuous at all, and thus there was no reason not to squeeze. However, to prevent this argument, we have implemented the controllers' individual calibration shown in the study section. The resulting strength needed to compress the controllers triggers a substantial discomfort after one minute at the latest. Furthermore, since we have found a significant difference in the period in which the controllers were pressed together, there was a reason not to press the controllers, which we believe is the exertion resulting from the interaction. Thus, we further assume that the reason for the non-observable difference in perceived exertion is the distraction of the VPA mechanic. In our study, pressing the controller together was performed while playing the game and did not require constant attention. Thus, our work differs from works in which, as in Born et al. [7], exertion mainly results from a continually changing interaction and requires constant attention. Our results are more resembling those of Mestre et al. [41] who used virtual worlds to successfully distract from the exertion resulting from training with rowing machines.

The high values of the General- and Spatial Presence subscale indicate that the high immersion of the VR system and the game have led to a high sense of presence. The lower Involvement values can be explained by the high body focus of the VR exergame. Involvement measures the degree to which the players paid attention to the virtual environment [51]. Since controlling the exergame was based on body movements, the focus could have shifted from the virtual environment to the exerting movements, leading to medium involvement values. Surprisingly, the experienced realism values are higher in the VPA condition than in the Points condition. While the VPA mechanic was implemented meaningfully, the points were just displayed as a number attached to the player's wrist. This could have disturbed the realism of the game. However, this result has to be interpreted with the low Cronbach's alpha in mind.

However, what surprised us most was that the players in the group without a motivator pressed the controllers together in more than 24% of the playtime, although this did not affect the game. According to the IPAQ, more than half of the participants showed the highest level of physical activity. Thus, the participants in our study could have a generally high motivation to voluntarily engage in strenuous activities and enjoy them. The positive correlation between the Interest/Enjoyment subscale and the IPAQ supports this assumption. Nevertheless, the time of pressing the controllers together seems to be independent of the participants' physical activity, which could be due to the individual adjustment of the spring strength at the beginning of each experiment. Another explanation for this finding could be found by considering gestural excess, which describes the movements of the body that are made while playing but are not relevant for controlling the game [1, 54]. Following the reasoning of Simon [54] gestural excess implicitly exists in the kinaesthetic dimension but can be foregrounded with specific devices such as the Wii. Our controller could have had such a high stimulating character due to its design that it triggered gestural excess in the players.

Furthermore, the players' main motives for pressing the controller together provide a good insight into the unexpectedly long duration of the pressing in the condition without a motivator. Pressing the controller together seems to have conveyed the feeling of being stronger in the context of the game, even if this was not the case as in the *Points* or *No Motivator* condition. Also, despite the increased exertion involved, the need to form a fist seems to have arisen in the game, as this seemed more authentic to a punching motion. Thus, there was a motivator to engage in the strenuous interaction even in the non-VPA conditions. Even though VPA had a stronger effect as a motivator, the controller seems to have a motivating effect in itself, especially in the game context. To further understand the players' motivation for engaging in the strenuous activity, future studies should also use qualitative measurements to get a more detailed insight on how players perceived the game, the gameplay, and the controller. This would allow drawing more accurate conclusions about the motivating elements of our setup, which could help future developments in their design decisions for voluntary exertion engagement. Further, we cannot make a reliable statement about whether the players perceived the interaction with the controller as strenuous. Here, future studies should either conduct preliminary research to test the controller in a neutral setting or further incorporate player perceptions into the study.

One limitation of the results is the small number of participants and a potential resulting reduced test power which could make it harder to draw clear conclusions and might have led to inflated effect sizes. Another limitation can be seen in the calibration of the device. The selected individual adjustment of the spring strength was intended as a fast approximation to the participant's physique to ensure that the interaction is equally strenuous for each player. Future studies should consider a more accurate calibration method that does not require adjustment by the participants themselves. In addition, most of the participants in our study show a high physical activity level. It would, therefore, be interesting in future work, with the basic idea of voluntary exertion, to select a sample of participants with a lower physical activity level. Furthermore, although our approach resulted in high motivation values and a long period in which the players voluntarily engaged in a strenuous activity, we cannot make a statement regarding the comparison to the classic exergame design, where the exerting activity must be performed to control the game. However, our results indicate that this comparison is worth looking into in future evaluations.

7 CONCLUSION

Our work has shown that using Virtual Performance Augmentation (VPA) as a motivator to perform an optional strenuous activity can significantly increase the period in which the strenuous activity was performed compared to using points as a motivator and to no motivator. Furthermore, we did not observe significant differences between groups for perceived exertion and interest/enjoyment. Nevertheless, since VPA could significantly increase the period in which the optional strenuous activity was performed, our results confirm the motivational nature and potential of VPA in VR exergames. Further, separating the need to execute a strenuous movement to play the game illustrates a possible direction for future research. Thus, it could be evaluated whether future games can generally motivate players to play the game and perform exerting movements voluntarily.

Furthermore, our work contributes to the future design of VR exergames that aim at meaningfully increasing the exertion without explicitly instructing players to perform them. Using a game mechanic such as VPA to reward the player for performing an optional exerting activity could serve as a new approach for (VR) exergames by supporting the players' autonomy and thus contributing to their intrinsic motivation.

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Abstract—**Exergames can increase cognitive performance compared to sedentary games and the same non-gamified exercise. Whether this advantage can be further enhanced by the high immersion and arousal level VR systems offer remains unclear. Therefore, we developed an exergame that can be played in VR or in front of a TV screen with identical gameplay in both versions. In a study with 32 participants, we collected data on cognitive performance, arousal, presence, motivation, and exertion. Our results show no difference in cognitive performance and arousal between the conditions. However, the VR version significantly increased players' presence and motivation while significantly reducing perceived exertion. Our results help to understand in which aspects VR can have a significant impact on exergames.**

Index Terms—**Virtual Reality, VR, Exergaming, Exergames, Exertion Games, Motivation, Cognitive Performance, Arousal**

I. Introduction

Exertion games or *exergames* are digital games "*[...] where the outcome of the game is predominantly determined by physical effort*" [31]. The use of exergames has demonstrated a positive impact in a variety of different domains, such as prevention and counteraction of childhood obesity [18], supporting physical rehabilitation [4] and improving cognitive performance [17].

While most of the exergaming research used older TV screen systems such as Microsoft's Kinect or Nintendo's Wii, current work focuses specifically on modern VR systems such as the HTC Vive. Since body movements serve as the main interactions, modern VR systems have an inherent exergaming property. Furthermore, first studies observed that in contrast to conventional non-VR exergames, VR exergames can improve central player experience related constructs such as motivation [6], [28] due to the high level of immersion VR systems offer. Thus, VR exergames are used for different purposes such as improving physical performance [2], decreasing perceived exertion [43], or supporting physical rehabilitation [19].

Beyond advantages that are directly linked to the context of physical activity, recent works used VR exergames to improve the cognitive performance of players [21], [26], [35]. For non-VR exergames, it has already been shown that exergaming can lead to better cognitive performance than playing a sedentary game [17] and performing the same gamified exercise [1]. Beyond that, the use of VR exergames can lead to enhanced cognitive performance compared to the same non-exergame physical exercise without VR [26], [35]. However, if the use of VR can enhance the cognitive benefits non-VR exergames provide remains unclear.

Therefore, we developed an exergame that uses either a conventional TV screen or an HMD as the output device but offers the same gameplay regardless of the output device. In a between-subjects design study with 32 participants, we investigated whether the VR exergame version could enhance the players' cognitive performance after a one-time training. In addition to cognitive performance, we measured the players' perceived and actual exertion, arousal, presence, and motivation to investigate their moderating effect on cognitive performance. Further, we used these constructs to investigate the impact of VR on player experience to support the research area with results from a between-subjects design study.

We did not observe a significant difference in arousal or cognitive performance between the conditions. Hence, we assume that the cognitive benefits exergames offer after a one-time training cannot be increased using VR. However, our results indicate that the VR version could significantly increase the players' motivation and presence while significantly reducing perceived exertion, although, as intended, actual exertion did not differ between the conditions. With our results, we address game developers and researchers alike. Our results support the insights on the comparison between VR and non-VR exergames. VR exergames but also conventional exergames in front of the TV (e.g., Nintendo's Ring Fit Adventure) are constantly developed further. Our results help identify areas in which VR systems can offer substantial benefits but also areas where VR may not further enhance the benefits exergames provide.

II. Immersive VR Exergames

Immersion can be defined as the extent of a user's technical integration into a virtual environment and is described as an objective characteristic of a technology [37]. Thus, modern room-scale VR systems offer a higher level of immersion compared to conventional screen systems. Immersion has a direct impact on the user's experience of presence [38] which can be defined as the feeling of "*being there*" [20] or simply as *presence*. In the context of exergames, a high sense of presence can significantly improve the player experience in various aspects.

VR exergames can significantly increase the player's experience of presence, self-efficacy, performance, and intrinsic motivation [6], [28] compared to non-VR exergames and to the non gamified version of the exercise [28], [43]. The player's intrinsic motivation, in particular, is a central construct in the context of VR exergaming since being intrinsically motivated can result in engaging in and enjoying a specific activity [34]. Moreover, on the one hand, VR exergames can reduce perceived exertion when used to distract from strenuous and repetitive exercises such as rowing or cycling [28], [43]. On the other hand, VR exergames that are driven by more complex and constantly changing interactions and thus do not require an exercycle or rowing machine can produce high motivation scores despite unreduced perceived exertion scores [6], [7], [16].

A. Exergaming, Arousal, and Cognitive Performance

However, beyond motivational benefits, which are directly related to the athletic context and the main focus of most studies on VR exergaming, exergames offer further benefits. One of these benefits is the improvement of cognitive performance through exergames [1], [17]. The positive influence of physical activity on cognitive performance has already been shown in various studies for a large number of different activities, intensities, periods, and target groups [11]. However, cognitive performance does not depend directly on physical activity but is influenced by arousal, which, among other things, is influenced by physical activity [24]. Arousal is defined as one of three dimensions of emotions besides valence [33] and dominance [29] and describes the excitation level of an affective state that ranges from calm to excited. In addition to physical activity influencing the arousal level, arousal can also be influenced by affective stimuli, such as pictures [25], sounds [9] or even game elements [30].

Beyond simple affective stimuli, the authors of [17] compared an exergame to the same game played sedentarily and to a conventional treadmill exercise. Although the exergame and the treadmill exercise induced similar physical exertion, the exergame induced more arousal. However, though the exergame showed improved cognitive performance compared to the sedentary game, no difference in cognitive performance to the treadmill condition could be found. Beyond that, the authors of [1] compared a three-month exergame intervention with a non-gamified version of the same athletic exercise. Although physical exertion did not differ between groups, the exergaming intervention significantly increased participants' cognitive performance. Unfortunately, the authors did not measure the participant's arousal as a potential moderator for cognitive performance. However, the results of [1] suggest that if the arousal level increases while physical exertion remains constant, the cognitive performance can be improved even more. With regards to the results of [17] and [1], the question arises how the arousal of exergames can be increased even further and whether an increase in arousal can benefit the cognitive performance even more, since for complex tasks, increasing arousal levels can decrease the cognitive performance after a certain arousal level is exceeded [42].

One way to further increase the arousal level in exergames is the use of VR. Several studies [10], [15], [32] observed increased arousal levels in VR games compared to non-VR games. Therefore, we hypothesize that the combination of VR and exergames can increase arousal through its physical exertion and high level of immersion. Thus, VR exergames have a potentially more substantial influence on cognitive performance compared to non-VR exergames. The influence of VR exergames on cognitive performance has been investigated in very few studies so far. The studies devoted to this topic have compared the effect of a VR exergame intervention with a control group that did not consist of a gamified version of the exercise. The authors of [35] compared a conventional training on a cycle ergometer to an exergaming version where the participants wore a Samsung Gear VR. Similar to the results of [1], the exergaming variant could lead to improved cognitive performance. However, the authors only compared a VR exergaming variant to the conventional non-gamified exercise but not a non-VR exergaming variant. Furthermore, the authors only measured cognitive performance and not arousal. In another work, the authors of [26] observed a positive effect of a VR exergame on older adults' cognitive performance above the age of 65 after a four-week intervention in contrast to no intervention.

The comparison between a VR and a non-VR version of an exergame regarding the effects on cognitive performance has been investigated by only one work so far. A recent study [21] showed that a VR exergame could lead to greater cognitive performance in people over 50 than a non-VR version of the game, but only after regular training over four weeks. However, the authors did not record the physical exertion as well as the arousal of the participants. Thus, it is difficult to determine whether the improved cognitive performance is due to the VR system's property or whether, for example, the physical exertion in the VR variant was higher than in the non-VR variant. Since the mere use of VR in the context of exergames can lead to increased exertion [41], it could be that the use of VR in the work of [21] increased physical exertion and thus influenced the cognitive performance. Furthermore, since only persons over 50 years of age participated in the study, it is particularly interesting to conduct further evaluations with a different age group, taking into account physical exertion and arousal. Moreover,

Fig. 1. The sword is 71 cm long, 16 cm wide, and weighs 356 grams with the HTC Vive Tracker attached. The shield has a diameter of 50 cm and weighs 829 grams, including the mount and the HTC Vive Tracker. While the sword is held in hand, there is a mount for the entire forearm on the shield's back.

since the author of [21] could not observe any effects for one-time training on the cognitive performance, but the work of [17] and of [35] could, the question arises whether the non-observable difference in the work of [21] is due to the high average age of the participants or the difference in the conditions compared.

B. Contribution

To gain a detailed insight into whether VR in the context of exergames can increase cognitive performance after a single training session and which factors can influence this, we developed an exergame that differs only in the output medium (VR vs. TV). To systematically evaluate which constructs are moderating this process, we record the constructs presence, motivation, exertion, and arousal in addition to cognitive performance in a study with 32 subjects. On the one hand, our results help to clarify the role of VR in enhancing cognitive performance in the context of exergames. Beyond that, our results also support the still relatively sparse research field comparing VR vs. non-VR exergames concerning central motivational and player experience-related factors.

III. VR Testbed Game

To investigate the difference between a VR and a non-VR exergame regarding their impact on the player's cognitive performance, we developed a new exergame with the game engine Unity. The game's setting takes the player to a small medieval village that Vikings have just plundered. As shown in figure 2, the player is standing at the end of a footbridge that leads from the village to a boat located behind the player. Vikings run toward the player to get on the boat and secure their loot. Besides, the opponents have occupied several positions in the village to throw skulls at the player. The players have to defeat the enemies running towards them and repel the skulls. For this, the players are equipped with a shield and a sword.

As shown in figure 1, we used padded weapons from the live-action role-playing domain for the shield and the sword. We mounted an HTC Vive tracker to both objects, using a clamp for the shield and a unique 3D-printed mount for the sword. The weapons are the only interaction objects in the game. The virtual representation of the weapons corresponds to the real ones. Since we wanted to develop a game that could be played in VR and in front of a conventional screen, the range of movements is severely limited if we want to compare the two conditions. However, to offer players a certain amount of exertion and interesting gameplay despite this limitation, we decided to use the real-looking interaction objects instead of lighter conventional controllers. Furthermore, in the context of VR, exergames using heavy controllers can increase the player's exertion while maintaining a high intrinsic motivation [7]. Since the interaction objects are mostly made of foam, they can be played with safely since even accidental hits of objects and body parts do not cause significant damage.

To keep the necessary movements identical in the VR and non-VR version, the players must perform all interactions with the shield and sword on the spot and do not have to walk across the room or rotate their vision. Hit enemies increase the player's score, while missed enemies decrease the score, which is displayed at a central location in the player's field of view, as shown in figure 2. To provide another motivational incentive, the player's striking power and the trajectory of defeated opponents continuously increase as the player consecutively defeats opponents. This mechanism is based on the idea of virtual performance augmentation from [22] and can increase intrinsic motivation in the context of VR exergames. The time intervals in which the enemies spawn shorten during the game time. Thus, the necessary exertion increases continuously. We have developed two different versions of the exergame, which only differ in the output device. In the VR condition, an HTC Vive Pro is used, while in the TV condition, a conventional Full HD 50 inch TV screen is used. We used a standard computer with a Ryzen 7 2700 CPU, 16 GB Ram, and an RTX 2070 Super GPU for both versions of the game. The gameplay and the interaction objects are identical in both conditions. Thus, we also use the HTC Vive trackers in the TV condition.

IV. Study

We conducted a quantitative study to evaluate the difference between the two versions of our exergame on cognitive performance and player experience.

A. Method

Cognitive performance was measured using the Stroop task [27]. In that task, participants are presented color words printed either in color the term stands for (congruent stimuli)

Fig. 2. A screenshot of the gameplay from the player's perspective.

or in a color that does not match the color's name (incongruent stimuli). Participants have to name the color the word is printed in and not the word itself. We used a computerized Stroop test provided by the *psytoolkit.org* website [39], [40]. Here, 40 color words were presented successively, and the participants had to press the corresponding button on the keyboard (e.g., for blue, they press "b"). We recorded the total reaction time, the reaction time for congruent and incongruent stimuli in seconds, and the number of errors. The arousal was measured by the Self-Assessment Manikin (SAM) [8] which includes one item for each affective state dimension (arousal, valence, dominance) that could be rated from 1 - 9.

To determine the perceived exertion, we used the Borg scale [5]. The scale asks for the sensation of exertion, which refers to the strain and fatigue of the muscles and the feeling of being out of breath and ranges from 6-20 (none - very, very hard). The actual exertion was assessed using the subjects' average heart rate during the baseline and gameplay phase. We used the *Bittium Biosignals Ltd. Faros 180* pulse belt. We used the Intrinsic Motivation Inventory (IMI) to measure the player's intrinsic motivation. The entire inventory comprises six subscales, of which the *Interest/Enjoyment* is considered the most significant one since it directly measures intrinsic motivation [14]. Beyond the *Interest/Enjoyment* subscale, we also assessed the *Perceived Competence* subscale and the *Pressure/Tension* subscale. Each subscale ranges from 1 - 7. The experience of presence was measured using the *IGroup Presence Questionnaire* (IPQ) [36]. The IPQ comprises the three subscales *Spatial Presence, Experienced Realism, Involvement* and the one item scale *General Presence*. Each subscale ranges from 0 - 6.

To consider the player's physical activity as a potential moderator for the assessment of the exergame and the player experience, we used the International Physical Activity Questionnaire (IPAQ) [13] to assess the player's physical activity level. There are two forms of output, a categorization of the participant's activity level (low, moderate, high activity) and a total value representing the weekly amount of energy expenditure carrying out physical activity. Furthermore, we used the Simulator Sickness Questionnaire (SSQ) [23] to assess if our setup causes simulator sickness. The resulting SSQ score can be between 0 and 235.62.

B. Design and Procedure

The study was conducted in a between-subjects design. Hence, each participant either played the TV or VR version of the exergame. We chose not to use a within-subjects design to prevent potential exhaustion, boredom, and fatigue of the participants. We deliberately did not include a third condition in which participants would have engaged in physical activity without an exergame, because a comparison between this variant and a non-VR exergame [1], [17] as well as to a VR exergame [26], [35] has already been studied in detail.

After arriving at the study site, the participants put on the pulse belt gave their consent to the study and completed questionnaires on demographics, prior experience with exergames and VR, IPAQ as well as the SSQ to check whether any high SSQ values after gaming were due to high SSQ values before gaming. During that starting period, we recorded the participants' heart rate to obtain a baseline heart rate, which we then could compare to the heart rate during the gameplay. The starting period depended on how fast the participant filled out the questionnaires but took around 7 minutes on average. Afterward, the gameplay phase started. First, the participants could then choose which hand they wanted to use for each controller. In the TV condition, the participants were positioned about 2 meters away from the screen. In the VR condition, they put on the HMD and were positioned at the center of a 3m *

2m play area. After finishing a tutorial on the basic gameplay, the participants started the game themselves. The gameplay in each condition lasted five minutes. We deliberately decided on a duration that falls between the duration of the works of [3] and [17], both of which examined arousal in exergames. During the gameplay phase, we recorded the participants' heart rates. Immediately after completing the game, the participants first completed the SAM and Stroop test. Subsequently, the SSQ, Borg, IMI, and IPQ were completed. The study ended with the participants being debriefed about the study. The study was compensated with one subject hour, of which up to 30 must be collected in the context of different study programs at our university. Since the Stroop test is based on colors, only participants without color vision deficiencies were allowed to participate in the evaluation. The ethics committee of our university approved our study. As the study took place during the COVID-19 pandemic, a special hygiene concept was developed and accepted by our university.

C. Hypotheses

Based on the assumption that VR applications can elicit higher arousal than non VR applications [10], [15], [32], we hypothesize that:

I *The VR condition leads to a significantly increased arousal compared to the TV condition.*

Since arousal can have an impact on cognitive performance [24] but can improve or worsen it depending on the height of the arousal level [42], we further hypothesize that:

II *The VR condition leads to a significantly different cognitive performance compared to the TV condition.*

Furthermore, due to the identical gameplay in both variants, we assume that:

III *The exertion in the VR condition is not significantly different from the TV condition.*

Based on the results of [6], we further assume that:

IV *The VR condition leads to a significantly increased experience of presence compared to the TV condition.*

V *The VR condition leads to a significantly increased motivation compared to the TV condition.*

D. Results

20 female and 12 male participants were included in the analysis ($N = 32$) and randomly assigned to one of the two conditions. Both conditions were assigned 16 participants each. The age ranges from $18 - 34$ years ($M = 22.6, SD = 3.12$). 59.38% of the participants reported having played an exergame at least once. 87.5% of the participants in the VR condition had no or just a little experience with VR systems, while the remaining 12.5% had at least five VR experiences. The IPAQ evaluation showed that the physical activity level of 6 participants can be rated as low, 13 as moderate, and 13 as high.

We calculated independent t-tests for the following group comparisons if normal distribution and variance homogeneity was given. If normal distribution was given, but no variance homogeneity was given, we calculated Welch t-tests. For both variants of the t-test, we used Cohen's d as the effect size measure. According to [12] the values of $|d| = 0.2$, 0.5, and 0.8 correspond to small, medium, and large effect sizes. If no normal distribution was given, we calculated Mann-Whitney-U tests and used the coefficient of determination R^2 as effect size measures. Values of $R^2 = 0.02$, 0.13, and 0.26 correspond to small, medium, and large effect sizes [12]. We calculated a mixed ANOVA with the condition as between factor and time of measurement as within factor for the heart rate. Normal distribution, equality of covariance matrices, and variance homogeneity were given. For the mixed ANOVA, we used eta-squared η^2 as the effect size measure. Values of $\eta^2 = 0.02$, 0.06, and 0.14 correspond to small, medium, and large effect sizes [12]. The variables relevant to the hypotheses are shown in figures 3 and 4. The remaining descriptive values, which are not represented in the figures, are shown in table I. The inferential statistical comparisons are presented in the following subsections.

TABLE I
MEANS AND STANDARD DEVIATIONS OF THE DEPENDENT VARIABLES WHICH ARE NOT PRESENTED IN FIGURES 3 AND 4

Subscales	VR M *(SD)*	TV M *(SD)*
IPQ		
Spatial Presence	4.33 (*0.95*)	1.93 (*1.34*)
Involvement	3.39 (*1.47*)	2.16 (*1.19*)
Experienced Realism	1.78 (*0.93*)	0.97 (*0.72*)
IMI		
Perceived Competence	4.10 (*1.16*)	2.58 (*1.28*)
Pressure/Tension	4.26 (*1.25*)	4.54 (*1.35*)
SAM		
Valence	7.26 (*1.61*)	5.25 (*1.88*)
Dominance	5.56 (*1.71*)	3.38 (*1.31*)
Stroop		
Incongruent Stimuli Response Time	27.6 (*6.08*)	26.7 (*6.04*)
Congruent Stimuli Response Time	8.64 (*2.42*)	9.33 (*2.97*)

*1) **Presence**:* A Mann-Whitney-U test revealed significantly higher *General Presence* values in the VR condition $U = 17.5, Z = -4.25, p < .001, R^2 = 0.56$. Further, t-tests revealed significantly higher values in the VR condition for the *Spatial Presence* $t(30) = 5.85, p < .001, d = 2.07$, *Involvement* $t(30) = 2.67, p = .012, d = 0.95$, and *Experienced Realism* $t(30) = 2.77, p = .010, d = 0.98$ subscale.

*2) **Motivation**:* A Mann-Whitney-U test revealed significantly higher *Interest/Enjoyment* values in the VR condition $U = 66.5, Z = -2.32, p < .020, R^2 = 0.17$. For the *Perceived/Competence* subscale, a t-test revealed significantly higher values in the VR condition $t(30) = 3.53, p = .001, d = 1.25$. No significant difference was found for the *Pressure/Tension* subscale $t(30) = -.60, p = .554, d = -.21$.

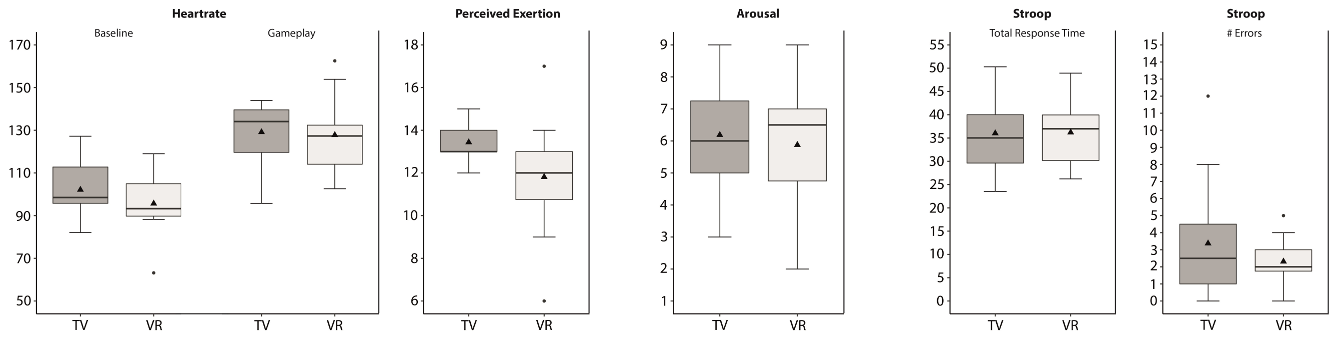

Fig. 3. Boxplots of the constructs relevant to hypotheses I-III.

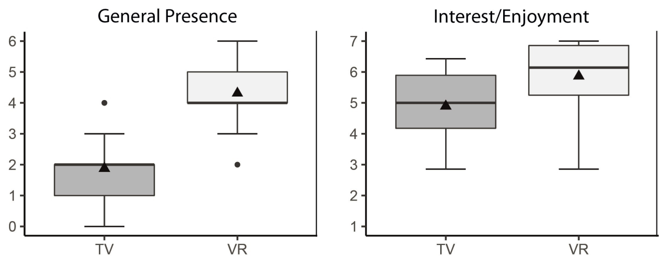

Fig. 4. Boxplots of the constructs relevant to hypotheses IV&V.

*3) **Exertion**:* For the Borg Scale, a t-test revealed significantly lower values in the VR condition $t(18.98) = -2.51, p = .021, d = -0.89$. For the heart rate we had to exclude nine participants since the pulse belt did not record data for these cases. A mixed ANOVA revealed no significant interaction between condition and time of measurement $F(1, 21) = 0.49, p = .490, \eta^2 = .004$. There was a significant main effect for time of measurement $F(1, 21) = 66.45, p < .001, \eta^2 = .481$ but no significant main effect for condition $F(1, 21) = 0.50, p = .487, \eta^2 = .008$.

*4) **Arousal**:* Mann-Whitney-U tests revealed significantly higher values in the VR condition for the *Dominance* $U = 39.5, Z = -3.39, p = .001, R^2 = 0.36$ and *Valence* $U = 43.05, Z = -3.28, p = .001, R^2 = 0.34$ subscale. However, a t-test could not reveal a significant difference for the *Arousal* subscale $t(30) = 3.53, p = .645, d = -.17$.

*5) **Cognitive Performance**:* With the exception of the Number of Errors, the following tests apply to all answers, regardless of whether they were correct or incorrect. Neither t-tests for the total response time $t(30) = 0.07, p < .941, d = 0.03$ and the response time of the incongruent stimuli $t(30) = 0.41, p < .684, d = 0.15$, nor Mann-Whitney-U tests for the response time of the congruent stimuli $U = 114.0, Z = -0.53, p = .598, R^2 < 0.01$ and the number of errors $U = 117.0, Z = -0.42, p = .674, R^2 < 0.01$ revealed significant differences between the conditions.

*6) **SSQ, IPAQ, and Correlations**:* The SSQ values in the VR condition before $M = 25.01, SD = 30.50$ and after $M = 29.20, SD = 36.72$ the gameplay are very low and give no reason to believe that simulator sickness has had a confounding influence. The IPAQ values do not significantly differ between the conditions $t(30) = -0.797, p = .431, d = -0.28$. Interestingly, we have found no correlations between the Stroop constructs and any of the other assessed subscales. However, beyond the cognitive performance, we have found correlations between the *Interest/Enjoyment* subscale and the *Spatial Presence* subscale $r(30) = .364, p = .041$, between the *Interest/Enjoyment* subscale and the *Borg* value $r(30) = -.363, p = .041$, and between the *Spatial Presence* subscale and the *Borg* value $r(30) = -.434, p = .013$.

V. Discussion

Our evaluation was motivated by whether cognitive performance following an exergame can be improved when the exergame is played in VR instead of in front of a TV screen. We considered arousal as a central moderator for the change in cognitive performance. We assumed that the use of VR could significantly increase arousal. We observed significant differences for the emotional dimensions valence and dominance, but not for arousal. Thus, we reject our first hypothesis. Hence, our results are not in line with [10], [15], [32], who found increased arousal levels in VR applications in contrast to non-VR applications. This leads to the question of why we could not observe this difference in our results. A possible explanation for this could be that the exergame used in our study already elicited arousal to an extent where the additional use of VR could not or only insignificantly increase the arousal level further. Moreover, the nature of the visual stimuli is crucial when it comes to the increase of arousal by VR systems [15]. Thus, our virtual environment's design and visual appeal could have just been perceived as not arousing. However, our VR exergame could significantly increase the experienced valence and dominance. Thus, we conclude that VR can substantially impact the player's affective response, but in the context of exergames, it has no impact on the player's arousal. Based on the results of [17], we, therefore, assume arousal is mainly influenced by the exergame regardless of the output device.

Similar to the arousal scores, the evaluation of the Stroop test reveals no significant difference between the conditions. We thus also reject our second hypothesis. Hence, according to our results, the player's cognitive performance after a one-time exergaming intervention does not seem to benefit from the use of VR. Thus, VR exergaming interventions that aim to increase the player's cognitive performance, such as in [35], mainly profit from the exergame and not from the VR system. As in [1], the exergame itself seems to have the most significant impact on cognitive performance, regardless of the output medium. Interestingly, our results are congruent to those of [21], although the game used, the target audience, the VR system, and the duration of the game intervention differ. Interestingly, however, the authors of [21] observed a positive impact of VR on cognitive performance after a 4-week intervention. Thus, although we conclude that VR can not improve cognitive performance after a single exergame intervention, VR could be beneficial for long-term exergame interventions that aim to support cognitive performance.

Besides the main question regarding arousal and cognitive performance, we have assessed the players' exertion, motivation, and presence to give a more detailed insight into the effects of VR on the player experience. The evaluation of the heart rate shows, as hypothesized, no significant difference between the conditions. It is noticeable that the baseline heart rate is relatively high in both conditions. This could be because we did not have a resting phase at the beginning of the evaluation in which the baseline was measured since we were not interested in the exact resting heart rate but instead in checking if the heart rate change in both conditions was similar. Interestingly, the evaluation of perceived exertion shows significantly lower values in the VR condition, although physiological exertion does not differ between conditions. Thus, we only partly confirm our third hypothesis. We assumed that, as in [6], perceived exertion shows the same tendency as actual exertion since our game does not require repetitive interactions such as rowing or cycling, which could be performed without a constant focus. Instead, the VR condition appears to have distracted from exertion as in the work of [28]. Since we have found negative correlations between the presence/motivation and the perceived exertion, our results suggest that also for VR exergames with constantly changing interactions, VR and the resulting presence and motivation can decrease the perceived exertion.

Furthermore, the evaluation of the IPQ reveals significantly higher values for all subscales in the VR condition than in the TV condition. Thus, the VR condition of the exergame led to a higher sense of presence. Our assumption that the VR system is more immersive than the TV system and thus leads to a higher presence is thus confirmed. Similar to the results of [6] the output device seems to have a significant impact on the experience of presence. We, therefore, accept hypothesis IV.

The evaluation of the IMI reveals higher scores for the *Interest/Enjoyment* and *Perceived Competence* subscales in the VR condition. Thus, the VR version of the exergame could lead to significantly higher intrinsic motivation than the TV condition. Hence, we also accept hypothesis V. Our results are in line with the findings of [6], [28] and confirm the positive influence of VR on players' intrinsic motivation in the context of exergames. Of particular interest is also the positive correlation between the Interest/Enjoyment subscale and the Spatial Presence subscale, which, in the context of exergames, was already observed by [7]. Since intrinsic motivation is the main object of investigation in most work on (VR) exergames, future research and developments should pay special attention to a potential connection between the players' presence and motivation.

A limitation of our work is that we only surveyed 32 participants, which could result in reduced test power. Also, our sample has few participants with a low physical activity level, which indicates a high basic motivation for physical activities and could thus have a particular impact on the assessed motivation. Moreover, the participants in our study were predominantly young, which makes it difficult to transfer our results to other age structures, especially in the context of cognitive performance. Thus, future studies examining the impact of VR exergames on cognitive performance should include a more diverse sample of participants regarding their age and physical activity level. Further, future studies should also vary the duration of the game and the type of physical movements, as both factors can have a substantial impact on cognitive performance [24]. Furthermore, future studies should measure more aspects of cognitive performance and use additional physiological parameters to measure arousal.

VI. Conclusion

Our study indicates that using a VR system instead of a conventional TV screen system does not benefit cognitive performance for a one-time exergame intervention. Moreover, our results suggest that while VR can enhance parts of the player's emotional response, arousal, as a vital moderator for cognitive performance, cannot be increased by the mere use of a VR system in the context of exergames. Beyond that, however, our results show that VR can significantly benefit the player's motivation and reduce perceived exertion. Particularly the player's experience of presence resulting from the high immersion the VR system offers seems to be linked with this increase. Our results help future developers as we show the benefits and limitations of VR systems for exergames. Future exergame developments that focus on player motivation should consider VR exergames, while exergames with the goal of increasing cognitive performance do not necessarily need to use VR to achieve a significant benefit.

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