DESIGNING VIRTUAL REALITY LABORATORIES FOR THE EVALUATION OF VIBROTACTILE WARNINGS

DISSERTATION

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Abstract

Virtual Reality (VR) provides researchers with a tool that allows them to recreate a wide variety of situations and scenarios virtually and use these virtual scenes for research purposes. Thus, VR offers the possibility to simulate immersive hazard scenarios and test them with people without putting the participants in real danger. By making it possible to virtually represent and immersively experience various domains and contexts, such VR laboratories (VR Labs) bridge the gap between laboratory and field testing.

This thesis explores the research question to what extent VR Labs are suitable for testing (directional) vibrotactile warning devices, focusing on the design requirements for VR Labs from a socio-technical perspective. As an application domain, construction site safety is used.

The fundamental challenge in the construction domain that this thesis addresses is the high number of accidents and fatalities in the industry. These are a consequence of many factors, such as time pressure, stress, workload, or the ever-changing work environment itself. The industry is trying to reduce the number of accidents and increase safety on construction sites, among other things, with safety training, safety inspections, and personal protective equipment. This thesis takes up the aspect of personal protective equipment and explores the idea of on-body directional vibration warnings of hazards, as is being researched for Proximity Warning Systems (PWS). Systems, such as PWS, can be viewed as augmenting human capabilities by alerting workers to hazards they may not be aware of. However, evaluations of such systems are often limited to technical components or laboratory testing since field testing could put participants at risk and would require extensive resources. Here, VR Labs allow testing such systems in an immersive, simulated work environment.

This thesis explores design aspects of VR Labs for evaluating directional vibrotactile warnings and construction site safety. First, the theoretical background is provided by discussing and referencing the contributions of cognitive psychology, the basics of tactile feedback, and relevant aspects of VR. Then, the design space is presented, and requirements are derived from a socio-technical analysis of the application domain, a conceptual design of vibrotactile wearables, and the translation of domain knowledge into the modeling of Virtual Environments (VE).

Then, several aspects of VR laboratories are reviewed in the subsequent studies. First, the extent to which the perception of vibrotactile cues in VR differs from that in reality and the impact this has on the choice of locomotion in VR is addressed. For this purpose, a proof-of-concept is presented to compare results made in VR with those from testing in real environments. Then, controller-based locomotion is compared to free movement in VR, and design recommendations are made based on the results and observations.

Based on the experiences made in the two studies, a study is presented on evaluating vibrotactile PWS in VR for hazard recognition and behavior adaptation. Here, directional

vibrotactile warnings are applied via a wearable attached to the waist of participants. This study highlights the need to include human factors in the development of PWS and discusses design aspects regarding the design of tasks, vibrotactile signals and patterns, and graphical fidelity of VEs.

Then, a study on VR safety training for experiential learning is presented. In this study, a simulation was used to teach the use of angle grinders and the associated safety aspects. The system was evaluated with trainees of the construction industry on learning effects, user experience, and usability. This study is followed by an analysis of social media data on the topic of VR-related accidents to provide insights into which safety aspects to consider when testing with VR. For this purpose, social media data from the platform 'Reddit' was downloaded and analyzed.

Finally, based on the experiences in the studies, a chapter on the design aspects of VR Labs discusses design recommendations and clarifies the socio-technical requirements of VR Labs. This chapter also provides multiple application scenarios for VR Labs, highlighting their flexible applications for research.

In conclusion, this thesis provides a broad understanding of design challenges and recommendations when designing VR Labs for the evaluation of directional vibrotactile warnings and construction site safety.

Zusammenfassung

Mit virtueller Realität (VR) steht der Forschung ein Instrument zur Verfügung, mit dem eine Vielzahl von Situationen und Szenarien virtuell nachgestellt und für Forschungszwecke genutzt werden können. So bietet VR die Möglichkeit, immersive Gefahrenszenarien zu simulieren und sie mit Menschen zu testen, ohne diese dabei realen Gefahren auszusetzen. Durch die Möglichkeiten der immersiven Darstellung von unterschiedlichsten Arbeitskontexten können VR-Labore (VR-Labs) die Lücke zwischen reinen Labortestungen und Feldversuchen schließen.

In dieser Thesis wird der Frage nachgegangen, inwieweit sich VR-Labs für die Erprobung von (richtungsweisenden) vibrotaktilen Warnungen eignen. Dabei stehen die Gestaltungsanforderungen von VR-Labs aus sozio-technischer Sicht im Vordergrund. Als Anwendungsbereich wird in dieser Thesis die Domäne der Baustellensicherheit herangezogen.

Eine der größten Herausforderung im Bauwesen, mit der sich diese Arbeit befasst, ist, die hohe Zahl von Unfällen und Todesfällen in der Baubranche. Diese sind eine Folge vieler Faktoren, wie Zeitdruck, Stress, Arbeitsbelastung oder das sich ständig verändernde Arbeitsumfeld selbst. Die Industrie versucht, die Zahl der Unfälle zu verringern und die Sicherheit auf den Baustellen zu erhöhen, unter anderem durch Sicherheitsschulungen, Sicherheitsinspektionen und persönliche Schutzausrüstung. Diese Arbeit greift den Aspekt der persönlichen Schutzausrüstung auf und untersucht die Idee der Warnung vor Gefahren durch gerichtete Vibrationen am Körper, wie sie für Proximity Warning Systems (PWS) erforscht wird. Systeme, wie PWS, können als Augmentation menschlicher Fähigkeiten verstanden werden, da Arbeiter vor Gefahren gewarnt werden, welche sie selbst vielleicht nicht bemerken. Die Testung solcher Systeme ist jedoch häufig auf technische Komponenten oder Labortests beschränkt, da Feldtests die Teilnehmer gefährden könnten und umfangreiche Ressourcen erfordern würden. Hier ermöglichen VR-Labore das Testen solcher Systeme in einer immersiven Simulation von Arbeitsumgebungen.

In dieser Arbeit werden Gestaltungsaspekte von VR-Laboren für die Evaluierung von richtungsabhängigen vibrotaktilen Warnungen und Baustellensicherheit untersucht. Zunächst wird der theoretische Hintergrund dargestellt, indem die relevanten Bereiche der menschlichen Informationsverarbeitung und der kognitiven Psychologie diskutiert werden, bevor die Grundlagen des taktilen Feedbacks und relevante Aspekte der VR behandelt werden. Anschließend wird der Gestaltungsraum dieser Arbeit vorgestellt, und die Anforderungen werden aus einer sozio-technischen Analyse des Anwendungsbereichs, einem konzeptionellen Entwurf von vibrotaktilen Wearables und der Umsetzung des Domänenwissens in die Modellierung von virtuellen Umgebungen abgeleitet.

In den anschließenden Kapiteln werden Studien präsentiert, welche mehrere unterschiedliche Aspekte von VR-Laboren untersuchen. Zunächst wird untersucht, inwieweit sich die Wahrnehmung von Vibration in VR von der in der Realität unterscheidet und welche Auswirkungen dies auf die Wahl der Fortbewegung in VR hat. Zu diesem Zweck wird ein Proof-of-Concept vorgestellt, um die in VR erzielten Ergebnisse mit denen von Tests in realen Umgebungen zu vergleichen. Anschließend wird eine Controller-basierte Fortbewegung mit freier Bewegung in VR verglichen, und auf der Grundlage der Ergebnisse und Beobachtungen werden Gestaltungsempfehlungen gegeben.

Basierend auf den Erfahrungen aus den beiden Studien wird eine Studie zur Evaluierung vibrotaktiler PWS in VR bezüglich der Gefahrenerkennung und Verhaltensanpassung präsentiert. In dieser Studie werden richtungsweisende vibrotaktile Warnungen über ein Wearable, das an der Taille der Teilnehmer befestigt wird, abgegeben. Diese Studie unterstreicht die Notwendigkeit, menschliche Faktoren in die Entwicklung von PWS einzubeziehen, und erörtert Designaspekte in Bezug auf die Gestaltung von Aufgaben in VR, vibrotaktilen Signalen und unterschiedlichen Vibrationsmustern sowie unterschiedlicher Grafiktreue von virtuellen Umgebungen.

Anschließend wird eine Studie über ein VR-Sicherheitstraining für erfahrungsbasiertes Lernen vorgestellt. In dieser Studie wurde eine Simulation verwendet, um die Verwendung von Winkelschleifern und die damit einhergehenden und zu beachtenden Sicherheitsaspekte zu vermitteln. Das System wurde mit Auszubildenden des Baugewerbes im Hinblick auf Lerneffekte, Benutzererfahrung und Benutzerfreundlichkeit untersucht. An diese Studie schließt sich eine Analyse von Social-Media-Daten zum Thema VR-bedingte Unfälle an, um Erkenntnisse darüber zu gewinnen, welche Sicherheitsaspekte bei der Nutzung von VR zu berücksichtigen sind. Zu diesem Zweck wurden Daten von der Plattform "Reddit" heruntergeladen und ausgewertet.

Auf Basis der gemachten Erfahrungen in den Studien werden zu den Gestaltungsaspekten von VR-Labs Gestaltungsempfehlungen diskutiert und die sozio-technischen Anforderungen an VR-Labs herausgestellt. Hierbei werden auch mehrere Anwendungsszenarien für VR-Labs vorgestellt, die die flexiblen Einsatzzwecke von VR-Labs für die Forschung unterstreichen.

Zusammenfassend präsentiert diese Arbeit ein umfassendes Verständnis der Gestaltungsherausforderungen und -empfehlungen bei der Entwicklung von VR-Laboren für die Bewertung von richtungsabhängigen vibrotaktilen Warnungen und Aspekten Baustellensicherheit.

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1 Introduction

In recent years, applying *Virtual Reality* (VR) has gained much attention in research and design due to the more powerful generation of cheaper and better consumer VR systems since the 2010s. It has since then been used to investigate all kinds of use cases, for example, VR training, therapy, simulations, and exergames, among others. Besides these scientific and industrial interests, developments in VR technology are driven by the entertainment industry (Jerald, 2016, p. 12). As a recent example, the gaming company *Valve*, famous not only for their game series *Half-Life*, published a new VR headset, the *Valve Index*, alongside their VR-*only* flagship game *Half-Life: Alyx* in 2020. Additionally, VR has gained much attention around the hype of the *metaverse*[1]. Although the concept of the metaverse is widely understood as a multi-technological way to interact with the internet, VR is highlighted as an access point to experience immersive content in the metaverse (S.-M. Park & Kim, 2022).

With VR, researchers can use all kinds of simulations through immersive experiences that isolate users from the real environment. This thesis is devoted to using VR as a method to evaluate and improve vibrotactile warning systems. Such systems warn workers of approaching vehicles or dangerous objects or places. They can be understood as an augmentation of human abilities (Raisamo et al., 2019). Several approaches for such systems can be found in the research literature. However, most are usually limited to a technical evaluation or as a proof-of-concept. The limitation to technical evaluations may result from the fact that, on the one hand, access to field testing on construction sites is not easy to solve, and, on the other hand, one would put participants at risk in such studies. Thus, conducting evaluation studies with participants in the field is hardly possible for safety and ethical reasons. As a result, such warning systems or prototypes are primarily tested in the laboratory or artificially created situations in the field rather than in the actual context of later use.

VR has the advantage of filling a gap between laboratory-only testing and field testing, as with VR, any environment can be replicated virtually. Thus, within immersive *Virtual Environments* (VEs), testing becomes possible in a demarcated space (laboratory) while participants are subjectively present in a virtual scenario.

This thesis uses VR to explore its capabilities to design and conduct evaluation studies of vibrotactile prototypes. The thesis focuses on the design of *VR Laboratories* (VR Labs)

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[1] The term *metaverse* was used by Neal Stephenson in his novel ‘Snow Crash’ to describe an immersive virtual world where humans interact with each other via avatars (Stephenson, 1992).

for research purposes and highlights their socio-technical requirements. The objective of applying VR Labs in this thesis is the field of *work safety* in the construction industry. For this, the thesis explores the evaluation and effectiveness of directional vibrotactile warnings and proposes how testing in VR Labs can improve vibrotactile warnings. The use case is explored using and replicating the example of *Proximity Warning Systems* (PWS) for construction work (e.g., Baek & Choi, 2018; Holden & Ruff, 2001) in VR. The underlying assumption for this research is based on the fact that access to field testing in hazardous areas, such as construction sites, is challenging. With VR, such fields can be simulated by placing participants into virtually constructed contextual environments without exposure to real hazards.

1.1 Motivation and Challenges

The motivation for this thesis is the exploration of possibilities to use VR systems as a research tool, not as a substitute for tests in real contextual environments or laboratories but as an addition, especially to pre-test technical prototypes in their respective context of use. VR gives researchers a tool that allows tracking and logging all kinds of events in a completely controllable (and customizable) environment (Clay et al., 2019, p. 1). Thus, research applying immersive VR can provide an increased *ecological validity* compared to other controllable but artificial laboratory environments (Loomis et al., 1999). Ecological validity refers to the extent to which observed behavior in laboratory settings can be generalized to the natural behavior in the world (Schmuckler, 2001). Enabling researchers to analyze behavior in such VEs might increase the ecological validity of results compared to an artificial laboratory setting. For this, VEs and VR have already been applied for research purposes to investigate various phenomena of human behavior. For instance, to treat panic disorder and agoraphobia (Botella et al., 2004), to recreate experiments like Milgram's Obedience Experiment with virtual avatars getting electrical shocks (Slater et al., 2006), to investigate bystander effects (Kozlov & Johansen, 2010), or to study the behavioral realism of social interactions in VEs (Herrera et al., 2018). Another area of application is the use of VEs in the automotive sector. Here, virtual simulations are used in driving studies, to investigate road and traffic safety to save engineering time and costs. Instead of having people drive in real cars on real roads, people drive in virtually simulated cars that reproduce real-world conditions (e.g., Blaauw, 1982; Reed & Green, 1999).

From a design perspective, VR enables researchers and designers to evaluate the design and functionalities of prototypes in their intended contextual environment of use. For instance, integrating wearable warning devices in hazardous scenarios to identify issues in the human-machine interfaces in early development phases. In the case of hazard warning systems, VR has the advantage that these systems can be tested with users virtually in an immersive and hazard-free environment of otherwise dangerous scenarios.

In this thesis, the context of use for VR is the evaluation and improvement of vibrotactile warnings in construction work. The context is motivated by several factors. First, the construction industry must cope with constantly high accident numbers, which are among the highest of all industries (e.g., Gibb et al., 2006; Haslam et al., 2005). Second, the construction industry must cope with high numbers of *fatal* accidents, also among the highest of all industries (Hoła & Szóstak, 2015). Third, VR is already researched for all kinds of projects in the construction industry and other contextual domains for safety training and education (e.g., Sacks et al., 2013). Using and evaluating vibrotactile warnings (for PWS) in an actual construction setting is challenging, as this would mean putting participants in dangerous situations. In addition, experimental testing in the field requires many resources in planning and conducting such tests. This thesis argues that with VR, researchers have an adequate tool to fill the research gap between laboratory and field testing and evaluate such systems during the immersive experience of vivid hazards. With further developments and the increasing use of *Building Information Modeling* (BIM) in the construction industry, it may be possible that daily updated 3D models of real construction sites can be used for such testing purposes. BIM uses digital representations of construction sites throughout the construction process (Borrmann, 2018) and is also used in construction site safety planning (Getuli et al., 2020; Sulankivi et al., 2009). Examples of how to include BIM data for VR have already been proposed (e.g., Du et al., 2018; Zaker & Coloma, 2018).

The application of VR Labs for the evaluation of vibrotactile warnings for construction site safety are explored from a socio-technical systems perspective. *Socio-technical Systems* emphasize that organizations should equally weigh social and technical factors (Mumford, 2000, p. 125). Thus, the domain of occupational safety on construction sites is analyzed from a socio-technical view to understand the design space and the processes within the domain. Finally, the design of VR Labs is presented from a socio-technical perspective as well as an exemplary socio-technical process for the operation of VR laboratories.

To summarize, the concept of this work is motivated by the potential capabilities to test and evaluate warning systems for safety-critical environments in VR-emulated hazard-free contextual environments. This thesis tries to fill a gap between laboratory evaluations and evaluations in the field. To achieve this, VR is used to simulate virtual construction site settings that can be used as test environments for vibrotactile prototypes. From this research, design recommendations and requirements for test environments are derived.

1.2 Research Questions

The research questions this thesis intends to answer relate to the design factors involved when considering VR simulations as a research tool for evaluating and improving vibrotactile warnings for the underlying domain of interest. In the case of this thesis, the field concerns construction sites, which can be understood as complex socio-technical environments. The characterization of construction sites to view them as socio-technical environments (or systems) is because there are many processes and interdependencies between technical and human resources. From the perspective of human factors, construction work requires a high level of workload, involves many distractions, and a high degree of dynamics in the work process, as described in Section 3.1.

RQ1: What design factors need to be considered to study vibrotactile cues in Virtual Reality?

Based on the theoretical background and related work in Chapter 2, this research question addresses three studies (presented in Chapters 4 and 5) focusing on several design factors for vibrotactile cues. The two studies in Chapter 4 investigate the impact of physical and artificial movement on the detection and recognition rate of vibrotactile cues. The study in Section 4.2 analyzes cognitive effort to react to vibrotactile cues with a Choice-Reaction Time (CRT) Task between movement in VR and a real environment. In contrast, the study in Section 4.3 analyzes reaction times to vibrotactile cues using real walking and an artificial controller-based locomotion in VR. The study in Chapter 5 investigates several other factors, such as visual fidelity, the dynamics of the virtual scene, the User Experience (UX), and the use of vibrotactile warnings in a scenario with multiple virtual hazards. Reoccurring design factors in all studies are the creation of an adequate task inside VR for such evaluation studies, the interaction design to use reaction times as a measure, and the modeling of an immersive experience in VR.

RQ2: What effect have vibrotactile warnings on hazard detection in VR?

This research question is the central question considering the extent to which perception-enhancing systems in human augmentation can warn of hazards and to what extent such evaluation approaches can be facilitated with VR Labs (Chapter 5). The underlying use case for this question is the use of vibrotactile proximity warnings in construction settings. This research question answers the extent to which VR Labs are suitable for evaluating vibrotactile warnings and how VR participants perceive and recognize virtual hazards.

RQ3: How does the warning detection compare for different vibration parameters (intensity and pattern) as warning signals?

This research question is investigated in the study on directional vibrotactile warnings presented in Chapter 5. In this study, several design parameters are used and varied, such as the vibration intensity, the duration of signals, the repetition, and the pause between signals. This research question adds to the research on designing vibrotactile patterns for warning purposes.

RQ4: What is the impact of experiencing a VR simulation on safety learning and safety knowledge?

This research question is investigated in a study on applying VR simulations for experiential learning as safety training (Chapter 6). The study was motivated by the results on vibrotactile warnings (Chapter 5), and the study focuses on the potential of VR for learning relevant safety aspects when working with construction tools. The study examines to what extent VR simulations are suitable as learning environments to be considered in such hazardous situations by investigating the UX and learning effects.

RQ5: How can a suitable VR Laboratory be designed to evaluate vibrotactile warning devices?

This overarching research question summarizes the observations and findings from the studies, focusing on the socio-technical design of VR Labs with the prospect of comparing results between VR and real environments. Based on the iterative design of the presented studies (in Sections 4.2, 4.3, and Chapter 5), the results from a previous study inform the design decisions of subsequent ones. Insights gained through this process are also part of the reported findings for this research question. Additionally, insights from the study on VR safety training (Chapter 6) are reflected and what safety aspects must be considered when using VR (Chapter 7). This research question addresses which components are necessary to successfully implement VR Labs, which personnel is needed to operate a VR Lab, and how it can be utilized for research.

1.3 Scientific Contributions

The dissertation contributes to several partly overlapping research areas for applied computer science and applied psychology, mainly Human-Computer Interaction (HCI), Human Factors Engineering, Engineering Psychology, Cognitive Psychology, and Socio-Technical Systems. Within this spectrum, the thesis addresses various topics of these research areas explicitly and implicitly: human perception and cognition, vibrotactile feedback for systems in terms of human augmentation, prototyping, and VR as a research and evaluation tool. The contribution of this dissertation is an exploratory methodological work on VR studies, mainly focusing warnings and safety, that combines vibrotactile warning research with VR. Regarding the contributions to the field of HCI presented by Wobbrock (2012; Wobbrock & Kientz, 2016), this thesis makes an artifact contribution by implementing vibrotactile wearables and VR scenarios, as well as a methodological contribution by demonstrating the utility of VR Labs for research on work.

The main contributions to VR research are:

- Outlining the design factors for the methodological use of VR Labs to investigate research questions in complex socio-technological phenomena such as construction sites.
- Showing how research with VR enables researchers to study human behavior in situations and environments that are difficult to access due to potential hazards without putting participants in any real danger.
- Use VR as an evaluation tool to test and assess the utility of new prototypes or future system ideas before complex hardware needs to be implemented.
- Providing an overview of necessary components for such research purposes and the socio-technical process of using the technology.

The main contributions to studies on vibrotactile warnings are:

- Outlining design factors to consider when testing vibrotactile feedback in VR.

- Results on the perception of different vibrotactile variables such as intensity, duration, delay, or repetition.
- Recommendations on building vibrotactile wearables and integrating them into VR simulations for evaluation purposes.
- Providing a prototypical technical solution for evaluating vibrotactile wearables in mobile and stationary (VR laboratory) settings.

1.4 Thesis Outline

The structure of this thesis, shown in Figure 1.1, is outlined as follows. After the introduction, Chapter 2 outlines the theoretical background addressing this interdisciplinary thesis's fundamentals and related work: human cognition and information processing, tactile feedback, and VR. Knowledge from the related work is used for the following design process to create artifacts and VR scenarios. Chapter 3 discusses the socio-technical design space, outlines the contextual parameters and requirements of the domain, and discusses the implementation processes for VR. Then, five research studies are presented:

- Chapter 4 presents two studies that investigate the perception, detection, and recognition of vibrotactile cues are presented. In the first study (Section 4.2), the influence of walking on the perception of vibrotactile signals is evaluated in VR and real environments. This study presents a proof-of-concept setup that allows the use of vibrotactile wearables in mobile and stationary settings. Findings from this study are used to iterate the design of the wearable and the VEs.
- The second study (Section 4.3) investigates the effect of locomotion techniques and interaction complexity on detecting vibrotactile cues and cognitive workload. The results of this study are used in the design of the third study on directional vibrotactile warnings.
- In Chapter 5, a third study explores and evaluates the utility of vibrotactile warnings for proximity warnings on construction sites by integrating several static and mobile hazards into the VE. The study focuses on how well participants notice different vibrotactile intensities and patterns and how the system supports hazard recognition.
- Chapter 6 presents a study that adds additional insights to the results from the study on proximity warnings in Chapter 5. Based on the observation of some unrecognized hazards and the occurrence of an accident in VR (see Section 5.9.4), this study explores the applicability of VR as a learning environment for safety training.
- Chapter 7 presents a study that was motivated by observations in the study on proximity warnings (in Chapter 5) and considers a phenomenon adjacent to the work. While the previous studies have dealt with the topic of work safety *in* VR, Chapter 7 addresses what safety aspects to consider when testing *with* VR.

Chapter 8 summarizes design recommendations and requirements when using such VR Labs for evaluation studies with VR. In Chapter 9, final remarks are made about the outcomes, limitations are discussed, the chosen method is reflected critically, and ideas for future work are outlined.

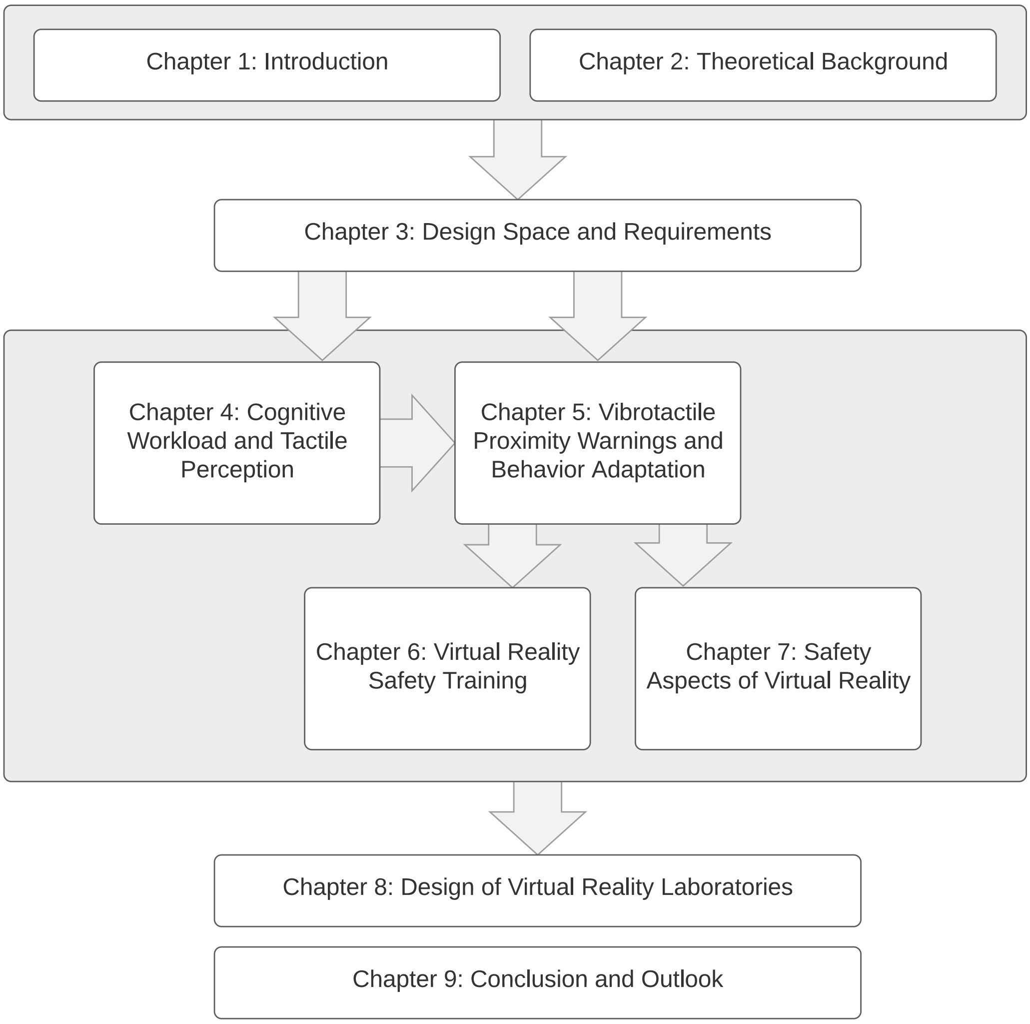

Figure 1.1: Thesis Structure

2 Theoretical Background

This chapter provides background knowledge and a review of related literature. The first subsection outlines the related background and theories for human cognition, perception, and information processing. Following this, reference is made to *Human Augmentation* as a research area focusing on enhancing human capabilities or compensating for limited ones.

The second part of this chapter focuses on tactile feedback. First, an overview of different tactile wearables and actuators is given. Then applications of tactile wearables are discussed before vibrotactile feedback for warning systems is addressed in more detail. The third part focuses on the topic of virtual reality. After introducing some basic concepts, the design space of interaction and movement in VR is discussed. This is followed by a literature overview of VR applications for scientific research and a reference to studies applying virtual simulations.

2.1 Contributions of Cognitive Psychology

This section addresses the fundamental contributions of human cognition to provide a basic understanding of information processing and sensory physiology that is relevant to understand VR use. Here, the tactile sense is briefly touched upon as a sensory channel, discussing the physiological fundamentals and psychological implications as an information channel (applications using tactile feedback and types of tactile feedback are focused on in the following Section 2.2). This section also addresses mental demand and multi-tasking and discusses the potential to substitute sensory channels for information transmission. These aspects of human cognition are essential to understanding and evaluating potential cognitive influences, and, how such effects have to be considered in VR simulations. Concepts such as multi-tasking are relevant to understanding the nature of distractions during work processes, how humans process information in such dynamic environments, and which design factors can contribute to better detecting (vibrotactile) warning cues. The section concludes by discussing human augmentation for future physiological, sensory, and cognitive enhancements.

2.1.1 Human Perception

To interact with and orient within our environment, humans have several senses that allow them to *perceive* environmental information and process it continuously (e.g., Sekuler, 2006, p. 1). Thus, a basic understanding of human information processing is also relevant for HCI and for designing human interaction with physical-, cyber-, or socio-technical systems (Card et al., 1983; Proctor & Proctor, 2021, p. 57).

A standard classification of human perception describes five different senses: vision (sight), hearing (audition), smell (olfaction), taste (gustation), and touch (somatosensory system) (e.g., Rosenblum, 2011). This classification can be traced back to the Greek philosopher Aristotle in his work *"De Anima"* (cf. Eysenck & Brysbaert, 2018, p. 37; Slakey, 1961), although, according to Geldard (1972), even then, Aristotle "*expressed some doubt on 'touch' as a single sense*" (p. 258). Besides this classical view of the human senses, we have senses that give us further information about our body, such as balance, experiencing pain or noticing temperature differences (Eysenck & Brysbaert, 2018, p. 38; Geldard, 1972). Thus, instead of limiting the sense on '*touch*,' sensitivity of the human skin is classified as part of the *somatosensory system.* The somatosensory system is classified into four submodalities: touch (mechanoreception), displacements of muscles and joints (proprioception), pain (nociception), temperature (thermoception) (Proctor & Proctor, 2021; Vallbo et al., 1979). The mechanoreception of the somatosensory system is of relevance to notice vibrations. Thus, it will be discussed further in Section 2.1.2.

Another sense relevant to humans is the vestibular system, sometimes referred to as "the sixth sense" (cf. Goldberg, 2012). The vestibular system is located near the inner ear cochlea, giving us a sense of balance and orientation of gravity, or in total, a sense of spatial orientation. It is of relative importance for VR research, as VR allows us to experience other (virtual) places and, thus, the vestibular system allows us to spatially orient ourselves in a completely artificial world (Viirre et al., 2001). The vestibular system is also relevant when experiencing *motion sickness* symptoms due to sensory conflicts (Goldberg, 2012, p. 12). As such conflicting input from the sensory systems occurs while using VR systems (e.g., moving artificially in the VE but sitting on a chair in the real world), the topic of motion sickness will be discussed in more detail in Section 2.3.1.3.

However, depending on the text and the authors, listings of senses might differ. For instance, authors might include senses providing information about the inner organs (visceroception) to the to the somatosensory system (cf. Treede & Baumgärtner, 2019). Then, one can discuss the relevance of senses at a higher level of brain functionality, like the moral sense, the sense of direction, or the musical sense (MacKenzie, 2013, p. 38), or one might group olfactory and gustatory senses to highlight that both are chemical senses (e.g., Hagendorf et al., 2011, p. 33; MacKenzie, 2013, p. 36). Thus, this text is not intended to serve as an exhaustive dispute of all human senses and their classification but to give an overview of the human sensory system, focusing on relevant ones for this thesis.

The information intake of sensory receptors is defined as *sensory sensation*. This intake of information is then translated by the brain, e.g., into sounds, images, or smells (e.g., Eysenck & Brysbaert, 2018, p. 38). In contrast, *perception* is defined as the interpretation of these sensations, thus, giving the sensation *meaning* (Wolfe et al., 2018, p. 4).

Processing information from multiple sense modalities simultaneously is called *cross-modal attention* (Eysenck & Brysbaert, 2018, p. 104). Cross-modal feedback refers to providing the same information via multiple senses, whereas *multimodal* feedback refers to providing different information via multiple senses (Hoggan et al., 2009).

Whereas sensation is an elementary and objective process, perception involves higher-brain functions, is subjective, and can vary between humans (e.g., Goldstein & Brockmole, 2017). For example, some stimuli might be physically painful for one human but not for the other. Understanding this distinction between sensation and perception is essential for HCI research, as participants might *perceive* and, therefore, subjectively value sensory input differently. This distinction is thus also relevant for vibrotactile stimuli, as parameters of vibrotactile sensations might influence the subjective evaluation, e.g., the sense of urgency. The *Gestalt Laws* (Wertheimer, 1923) exemplify the importance of understanding human perception, as these laws (or guidelines) have been applied in the design of interfaces. For instance, the law of proximity refers to visually grouping elements that belong together (e.g., Eysenck & Brysbaert, 2018, p. 41).

Detecting sensory stimulation or detecting the difference between stimuli depends on perceptual *thresholds* (e.g., Proctor & Proctor, 2021, p. 59; Wolfe et al., 2018, p. 6f.). Here, an *absolute threshold* indicates the minimum amount of sensory stimulation that is needed to detect a stimulus. A *difference threshold* defines detecting the slightest changes between two stimuli or detecting a minimal change of one stimulus to distinguish it from a reference stimulus. For touch, the *two-point touch threshold* describes the smallest distance between two points to be perceived as two and not only one point of touch (E. H. Weber, 1996). As the two-point touch threshold is of interest for vibrotactile feedback on different body parts, it will be discussed in the following section on tactile perception (Section 2.1.2).

Closely related to the perception of stimuli, humans can adapt their perception to filter out reoccurring and not changing stimuli. *Habituation* and *sensory adaption* are the processes that lead to ignoring the stimuli (Ciccarelli & White, 2017, p. 136). Whereas habituation occurs when a reoccurring stimulus does not change over a more extended period and the brain starts filtering out signals from these receptors, sensory adaption refers to the "tendency of receptor cells to become less responsive to a stimulus that is unchanging" (Ciccarelli & White, 2017, p. 136). An example of habituation is the constant exposition to noise caused by nearby railroad tracks. The more often one is exposed to the stimulus of train noise, the less noticeable it becomes over time - until, at some point, a visiting guest might point out the train noises as they are not permanently exposed to the stimulus and, as a consequence, the stimulus is again noticeable for some time. For comparison, an example of sensory adaptation is the taste of food. The first taste has more detectable flavors than the following ones.

Understanding the perception and habituation of stimuli is relevant for studying tactile feedback systems, as habituation to such signals would reduce their impact and usefulness. Another concept related to being exposed to many stimuli is the phantom stimulus, a perceived but nonexistent stimulus. Primarily known as *phantom vibration*, smartphone users may sometimes perceive a vibration of their smartphone, even if it does not vibrate (also *phantom vibration syndrome*). The same applies to *phantom ringing* (Deb, 2015). Although these vibrations are not bothersome to the higher number of users, their prevalence is remarkably high, as in a study with undergraduates, around 90% of participants mentioned having experienced phantom phone vibrations (Rosenberger, 2015). Kruger and Djerf (2017) argue that phantom ringing and vibrations are a symptom of psychological dependency on cell phone communications. For instance, their results showed that students that self-reported a higher tendency to be cell phone dependent were experiencing phantom vibration more often (Kruger & Djerf, 2017). However, the empirical data on phantom vibration remains limited (Rosenberger, 2015).

2.1.2 The Tactile Sense

In 1957, Geldard presented an application of the tactile sense with the vibrotactile language "*vibratese"*. By systematically using three dimensions of vibrations (amplitude, duration, and location), he designed 45 basic elements for the language (Geldard, 1957). Since then, considerable research (in HCI) has been focusing on tactile applications and presenting information via the tactile sense to users (Bergström & Hornbæk, 2020; Chouvardas et al., 2008). The application ideas are based on sensory substitution, e.g., for the blind and visually impaired (e.g., Bliss et al., 1970; Edman, 1992), to use the skin as communication channel (e.g., Saunders, 1983), or to distribute information over multiple sensory channels in *multimodal interfaces* (L. A. Jones & Sarter, 2008). Another justification for using the tactile sense is that it might still be responsive when other senses are not, e.g., in highly noisy or visually distracting environments (van Veen & van Erp, 2001). Research utilizing tactile feedback for various use cases and applications are outlined in Section 2.2.5.

The skin is understood as the largest organ of humans (cf. Montagu, 1986, p. 6) and is part of the outer layer of bodies, the *integumentary system* (Mauldin & Peters-Kennedy, 2016). For sensory perception, the skin uses *cutaneous* inputs from mechanoreceptors and thermoreceptors, and *kinesthetic* inputs from mechanoreceptors in muscles, tendons, and joints (Lederman & Klatzky, 2009). The skin divides between *hairy* or *glabrous* (non-hairy) skin (see Figure 2.1). Distinguishing both classes is relevant, as "they vary in sensory receptor systems and measures of tactile sensitivity" (Hoggan & Brewster, 2012, p. 216). For perceiving tactile stimulations, four different mechanoreceptors have been identified for the somatosensory system that responds to pressure, vibration, or movement: Meissner corpuscle (RA), Merkell cell (SAI), Pacinian corpuscle, and Ruffini endings (see Table 1). They locate in the outer and visible layer of the skin, the epidermis, and the layer beneath, the dermis. (cf. Hoggan & Brewster, 2012; Wolfe et al., 2018).

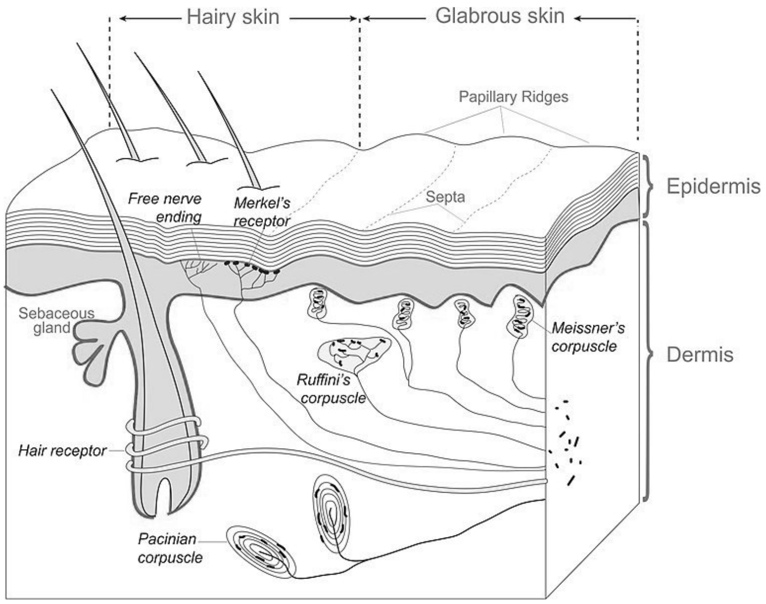

Figure 2.1: Anatomy of human skin and its receptors (Thomas.haslwanter, 2019)

Sensitivity for tactile perception differs among the human body. The *two-point touch threshold* or *two-point discrimination* (2PD) classifies the smallest spatial distance between two stimuli that are presented simultaneously to the skin that is, subjectively, recognized as two different stimuli and not as one (e.g., Lederman & Klatzky, 2009, p. 1441). The two-point touch threshold was published by E. H. Weber in his work "De Tactu" in 1834 (E. H. Weber, 1996) and has been used to understand the differing tactile sensitivity of the human body. For example, the 2PD of a human forehead is smaller than the threshold of a forearm, meaning it is easier to interpret the stimuli as two different ones on the forehead than on the forearm. Such information is relevant when designing vibrotactile systems by incorporating tactile spatial acuity.

Table 1: Mechanoreceptors (adapted from Wolfe et al., 2018, p. 424f)

Receptor	Functionality	Sensitivity
Merkel cell neurite complex	Texture perception Pattern/Form perception	Sustained pressure, very low frequency (< ~5Hz)
Ruffini endings	Stretching of Skin, Finger position	Sustained downward pressure (low sensitivity to vibration) lateral skin stretch
Meissner's Corpuscle	Low-frequency vibration detection Stable grasp	Temporal changes in skin deformation (~5-50 Hz) Skin slip
Pacinian Corpuscle	High-frequency vibration detection Fine texture perception	Temporal changes in skin deformation (~50-700 Hz)

2.1.3 Information Processing and Attention

An objective of cognitive science is to understand human information processing. To understand and discuss the information processing of sensory information, researchers have used flow diagrams and process models to propose and visualize models of information processing, analog to the visualization of how computers process information (e.g., Radvansky et al., 2014, pp. 16–20). Using diagrams and processes to visualize these kinds of information-processing tasks helps to understand the human mind when developing applications and prototypes for various contexts. In the 1950s, psychologists used the analogy of computers and laid out the foundations for visualizing information processes in stages (cf. Goldstein & Hooff, 2020, p. 12).

One example of such a process model was proposed by Atkinson and Shiffrin (1968), also referred to as the *'Standard Theory' of memory* (cf. Radvansky et al., 2014, p. 23). In this process model, Atkinson and Shiffrin (1968) distinguished between a short-term storage of information in the human brain, or temporary working memory, and a long-term storage, as permanent memory storage (see Figure 2.2). The basis for this model is the assumption that short-term memory has a limited capacity to store information. The bi-directional relation between short-term and long-term memory shows that some information must be recalled from the long-term memory into the temporary working memory to find an adequate response output.

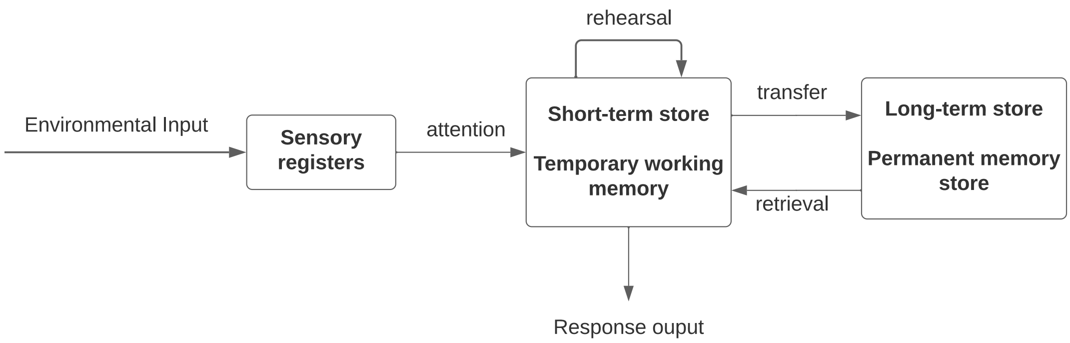

Figure 2.2: Standard Theory of Memory by Atkinson and Shiffrin (1968). Figure adapted from Radvansky et al. (2014, p. 23)

A basic understanding of information processing is essential for this thesis. It is necessary to understand how (vibrotactile) warnings must be designed so that they are perceived and understood while performing other tasks. Thus, the following subsections discuss relevant models for information processing and task performance.

2.1.3.1 Wickens' Model of Human Information Processing

A model of human information processing that integrates attentional resources is the model of human information procession proposed by Wickens (2002). The model incorporates the flow of information between sensory perception, cognition, and action. It also integrates the information process into the broader contextual environment. On the left side, the model starts with the stage of sensory processing of perception. The perception of sensory information also incorporates past experiences from long-term memory. After the stage of perception, signals follow one or both paths. Sometimes, perception might lead to a direct response, e.g., when reflexes are triggered. Other times perception might need the higher cognitive function to recall resources from memory.

Wickens' model adds attention and feedback to the standard theory model. Feedback refers to changes in the environment that are based on the response of the human. Attention refers to either filtering or selecting information that one perceives. The filtering mechanism leads to a selection of information chunks for further processing. In contrast, the fueling mechanism leads to actively focusing on sensory information that has to be processed.

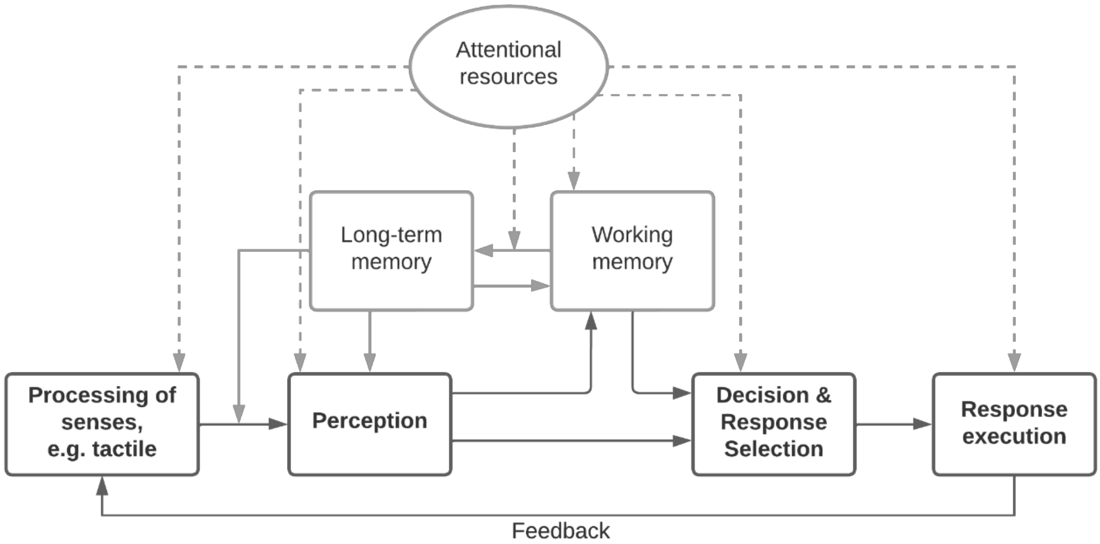

Figure 2.3: Human Information Processing Modell, adapted from Wickens et al. (2013, p. 22)

Such models are crucial to understanding the cognitive information processes of human beings and are used in the design and development of cognitive systems. Humans can filter out sensory input to focus on a specific input. This *selective attention* works like a filter to choose between multiple sources or channels of information (e.g., Wickens & Carswell, 2021). The channel to attend depends on the *salience*, *effort*, *expectancy*, and *value*:

- Salience refers to how one specific stimulus stands out from others, i.e., a colored object in a black-and-white picture will capture the attention, or a car horn might capture a pedestrian's attention.
- Effort refers to a human's effort to scan and move attention to the environment, i.e., a fatigued driver may not check the blind spot when changing lanes.
- Expectancy describes the knowledge regarding the available information of time and location, i.e., a driver would focus more on a curvy road while driving fast than on a straight road while driving slowly.
- Value refers to the perceived usefulness or importance of the received information, i.e., a high number of different advertising signs along the road might have a high expectancy but no value and, therefore, might receive little to no attention (cf. J. D. Lee et al., 2017; Wickens & Carswell, 2021; Wickens & McCarley, 2008).

Applying the model to the design of vibrotactile warnings highlights several requirements: the warnings must stand out clearly (salience), assist human workers in detecting hazards in a timely manner (effort and expectancy), and be appropriately helpful in noticing hazards (value).

2.1.3.2 Communication-Human Information Processing Model

Wogalter et al. (1999) have proposed the *Communication-Human Information Processing* (C-HIP) model in the literature on (visual) warning research. The C-HIP model combines the basic human communication model with information processing (e.g., Wogalter, DeJoy, et al., 1999; Wogalter et al., 2021). Three communication components are used inside this model: a *sender* (or source), a (communication) *channel*, and a *receiver*. The receiver needs to process the communication message given by the sender:

- Notice the message and shift attention toward the message.
- Interpret and comprehend the message.
- Based on attitude and beliefs, evaluate the relevance of the warning message to motivate adequate behavior in response to the warning.

Whereas the information flow in the C-HIP model is linear, it also integrates feedback loops to show that information in the later stages impacts earlier ones. The source in this model represents the transmitter of the hazard information, which might influence the effectiveness of the warning. The channel relates to the information channels used to transmit the message (singular or multiple), including all available sensory channels.

Beginning with the stage delivery, the information process in the model outlines the internal processes of the receiver:

1) The message can only be processed if it is noticed by the receiver and by shifting attention toward it.
2) Memory capabilities must allow processing information to comprehend the meaning of the message.
3) The receiver's attitudes and beliefs toward the message are relevant to motivating the receiver to comply with the warning message.

First, the message can only be processed if it is noticed by the receiver and by shifting attention toward the message. Second, memory capabilities must allow us to process information to comprehend its meaning. Third, personal attitudes and beliefs that the receiver has towards the message are of relevance to motivate the receiver to comply with the warning message. Only then can the desired outcome of safe behavior be achieved (Wogalter, DeJoy, et al., 1999, pp. 14–16; Wogalter, 2006, p. 24, 2018, pp. 34–43). In a later and updated version of the C-HIP model, Wogalter included the stage of message *delivery* between channel and receiver, which might be impacted by *other environmental stimuli*. The stage of delivery refers to the way *how* the warning message is transferred via the channel. Other environmental stimuli refer, for example, to other objects, people, etc., that are in the environment of the receiver and might therefore compete with the receiver’s attention (Wogalter, 2018, pp. 33–43).

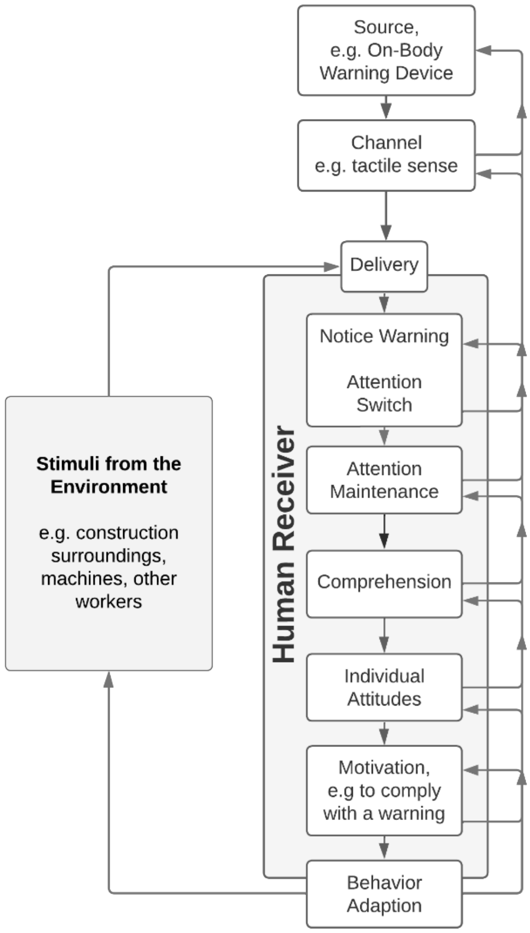

Figure 2.4: C-HIP Model, adapted from Wogalter (2006, p. 52)

Based on this research, Wogalter (2006) lists four components that a warning message requires:

- **Source**: Origin of the given warning.
- **Medium/Channel**: Media and sensory channels that are used to deliver the message from the source to the receiver.
- **Message**: Includes relevant information about the hazard and instructions on how to cope with the hazard.
- **Receiver**: Entity that should receive and be informed of the warning.

Based on the model of human information processing, the C-HIP model states that it must be ensured that humans (receivers) can understand the origin (source) of a vibrotactile (channel) warning (message) in order to respond adequately.

2.1.3.3 Multiple Resource Theory

Humans are able to divide their attention up to a certain point and do multiple things at once, sometimes referred to as *multi-tasking*. However, there are limitations when processing multiple things simultaneously, and performing multiple tasks can have varying degrees of success. For example, while driving a car, a human might be able to talk to a passenger, whereas it becomes more difficult (and dangerous) for the same human to write a text message on a mobile phone while driving. According to the *Multiple Resource Theory* (MRT), tasks that use “different resources interfere less with each other than tasks using the same resources” (J. D. Lee et al., 2017, p. 190). In the given example, the tasks of listening and talking to a passenger while driving, meaning auditory and visual-spatial resources, compete less for the same resources compared to the tasks of writing while driving, which both require visual-spatial resources (J. D. Lee et al., 2017, p. 190). The MRT assumes four “categorical and dichotomous dimensions that account for variance in time-sharing performance” (Wickens, 2002, p. 163). The four dimensions are modalities of perception, stages of processing, visual channel, and codes of processing (Figure 2.5).

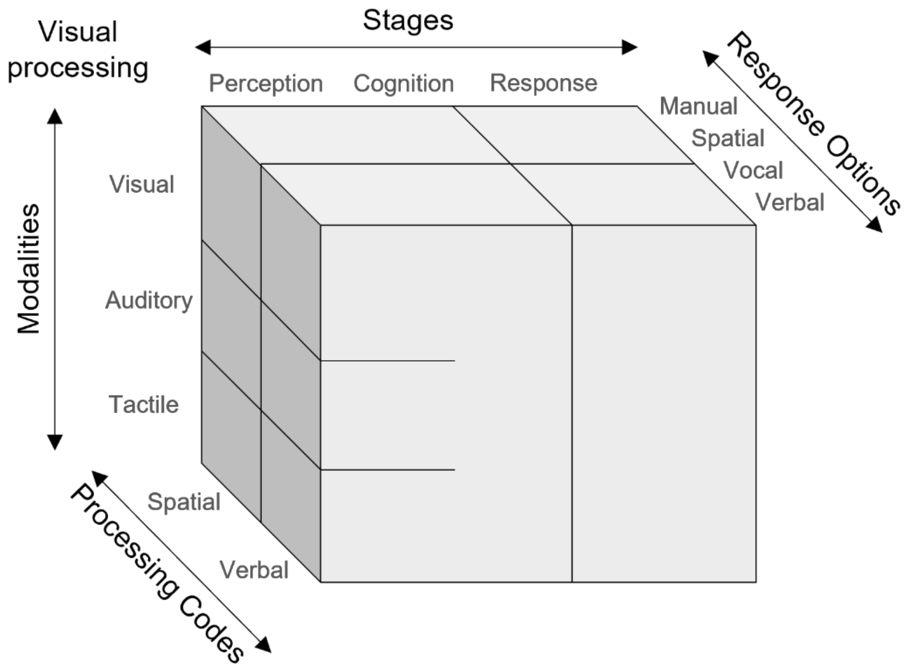

Figure 2.5: Multiple Resource Theory Model (adapted from Wickens et al., 2013, p. 294)

The modalities refer to the sensory modalities: auditory, visual, and tactile. Stages refer to the processing stages of the information: perception, cognition, and response. The dimension of visual processing refers to two different aspects of vision: *focal* and *ambient* vision. Focal vision is required for object recognition, for instance, when reading, whereas ambient vision is used for peripheral vision, for instance, while driving straight.

The MRT gives a basis to understand what challenges a VR Lab has to address for the evaluation of vibrotactile warnings and what challenges workers face on construction sites. Being aware of one's own safety on construction sites and being wary of hazards requires the visual-spatial resources that are also needed when performing construction work. As such, the MRT also provides a good basis for shifting warnings to the tactile modality. For construction activities, there is less demand on the tactile modality then, in contrast, on the visual-spatial or the auditory modalities.

2.1.4 Mental Workload

The amount of mental resources a task requires is defined as *Mental Workload*. The concept is related to the multiple resource theory, but according to Wickens, often confused, as they overlap but are distinct (cf. Wickens, 2008, p. 452). Whereas the MRT focuses on demand, resource overlap, and allocation policies, mental workload is limited on the demand of tasks. Mental workload and mental load are also often used synonymously to *Cognitive Load* (Galy et al., 2012; Schnaubert & Schneider, 2022) or to *Cognitive Workload* (e.g., von Janczewski et al., 2022).

However, the term "cognitive load" is also strongly tied to the *Cognitive Load Theory* (CLT), and is defined as mental activities required to process information (Cooper, 1990; Sweller, 1988, 2018). The CLT is a theoretical framework to understand resource allocations and attention demands for educational learning. Sweller (1988) distinguished three categories of cognitive load: intrinsic load, germane load, and extraneous load. *Intrinsic load* refers to the mental load of the task or learning entity itself. For instance, learning a poem by heart is more complex than memorizing one word. *Germane load* refers to the resources that are needed to learn. For instance, presenting information that incorporates known schemas might reduce germane load and increase learning. Finally, *extraneous load* refers to the environmental surroundings unrelated to intrinsic and germane load (Paas, Renkl, et al., 2003; Paas, Tuovinen, et al., 2003; Sweller, 1988, 2018).

The concepts are important for HCI and today's information systems, as, for instance, having to handle a poorly designed and complex user interface of a learning platform might increase extraneous load compared to a platform with an easy-to-use interface (e.g., J. D. Lee et al., 2017). Additionally, poorly thought-out designs can lead to confusion and cognitive overload of users (Albers & Tracy, 2006; Hollender et al., 2010).

There are several ways to measure mental/cognitive workload. For instance, the consequence of a poorer task performance due to increased workload is utilized in the *dual-task paradigm*. While participants fulfill a primary task, their performance in a simultaneously executed secondary task is measured (Schoor et al., 2012). This requires an initial measurement of participants' performance in the secondary task as a *baseline measure* to compare the baseline measure with the performance measure while executing both tasks. An advantage of the dual-task approach is "that it is a concurrent measure of cognitive load as it occurs" (de Jong, 2010, p. 118)

An example of such dual-task is measuring *Reaction Times* (RT) in a secondary task. In RT tasks, participants have to respond to a randomly reappearing cue while performing another task, also known as *Stimulus-Response Task*. A *reaction time* (or response time) is hereby defined as the time elapsed between the appearance of the cue and the point of response by the participant (see Figure 2.6). RT measurements have a long history in (cognitive) psychology and rely on the assumption that mental processes require time (e.g., Harald Baayen & Milin, 2010; Radvansky et al., 2014, p. 20). The literature holds many examples of RT studies. For instance, research has shown that reaction times become slower with increasing age (Deary & Der, 2005).

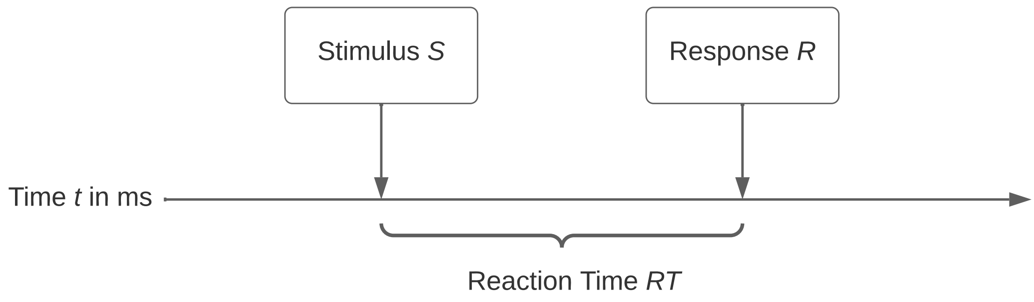

Figure 2.6: Example of a Reaction Time Measurement

Applying reaction time measurements, Sklar and Sarter (1999) have shown that tactile feedback can effectively indicate unexpected changes in complex and attention-allocating work environments. In their study, they compared RTs to visual, visual and tactile, and tactile feedback while participants followed three equally essential tasks in a flight simulator: monitoring for unexpected mode transition and traffic conflicts and deviations of an engine parameter. Results have shown that participants reacted significantly slower to transitions when receiving only visual feedback. In contrast, both tactile conditions led to higher detection rates and faster reaction times (cf. Sklar & Sarter, 1999, p. 549f.).

Besides such performance measures, mental workload can be measured with subjective questionnaires or psychophysiological measures (S. Chen, 2017; Galy et al., 2012). Examples of psychophysiological measures are brain activity measures (e.g., fMRI, EEG) or heartbeat recordings. Subjective measures are self-report questionnaires. Commonly used questionnaires for surveying cognitive load are the *Nasa-Task Load Index* (Nasa-TLX) (Naismith & Cavalcanti, 2015) or the *Paas Scale* (Paas, Renkl, et al., 2003; Paas, Tuovinen, et al., 2003). Although the Nasa-TLX was initially introduced as a questionnaire to assess overall workload (Hart, 2006; Hart & Staveland, 1988), its item 'mental demand' is often used when assessing cognitive load (Naismith & Cavalcanti, 2015).

Understanding the concept and measurement of mental workload is essential when evaluating within VR, as the workload might differ between real conditions and VR. Due to the needed VR hardware and software implementations, tasks in virtual scenarios might only include some relevant details of (real) tasks. Additionally, using VR hardware for locomotion and interaction in virtual scenarios might already lead to differences in mental workload compared to comparable scenarios in the real world.

2.1.5 Amplified Perception: Human Augmentation

Combined with the understanding of human perception and cognitive abilities, the development of new technologies led to the research of substituting or extending these human abilities. Human Augmentation (HA) focuses on enhancing, expanding, and compensating human physical and psychological capabilities by applying technological advancements (Alicea, 2018; Kenyon & Leigh, 2011; Raisamo et al., 2019). With the rise of new technologies, more powerful sensors, algorithms, or better artificial intelligence, technology can outperform human senses in many ways (cf. Schmidt, 2017). According to Schmidt (2017), there are two main directions in how to augment human perception: by “enhancing and amplifying existing senses” and by “extending perceptual abilities […] where humans have no perception but technical sensors exist” (p. 8). The amplification of human perception and cognition in closely coupled human-technology systems follows to some extent the idea of “super-human abilities” (cf. Schmidt, 2017) with abilities of perception that go far beyond standard human capabilities (Figure 2.7).

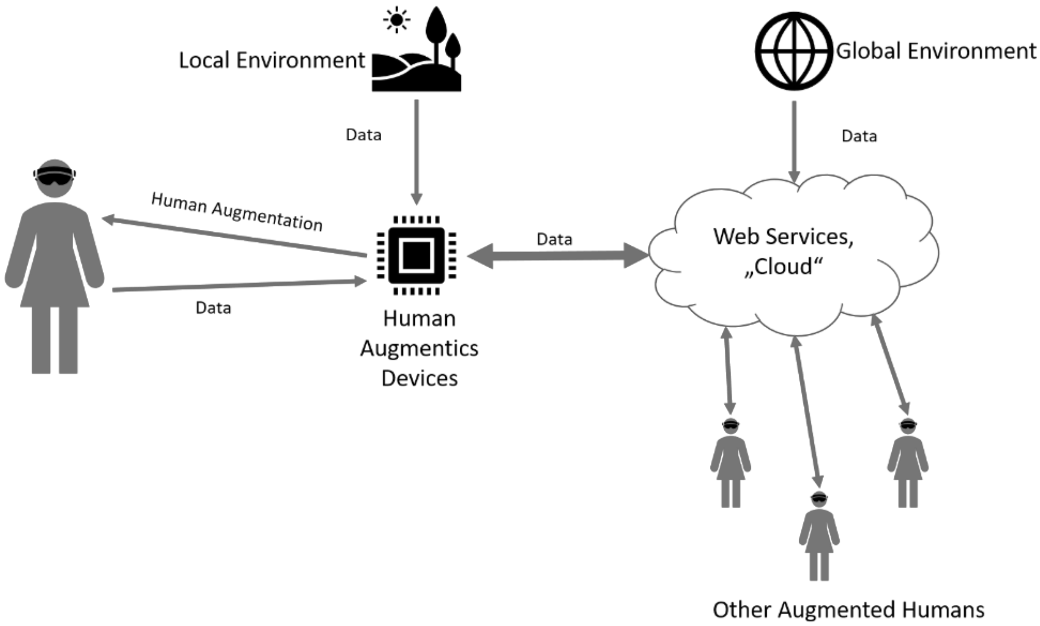

Figure 2.7: Abstract model of a Human Augmentation, adapted from Kenyon and Leigh (2011)

For the purpose of definition, Raisamo et al. (2019) refer to HA as “an interdisciplinary field that addresses methods, technologies and their applications for enhancing sensing, action and cognitive abilities of a human” (p. 4). The authors identified three categories of HA, including the view on human action:

- *Augmented Senses,*
  by interpreting multisensory information and presenting this information to the human through selected senses.
- *Augmented Action*,
  by sensing human actions and translating (or “mapping”) these actions to local, remote, or virtual environments. The authors also include subclasses to augmented action, e.g., motor augmentation, speech input, or teleoperation.
- *Augmented Cognition*,
  by using analytical tools to interpret human cognitive states and adapt to the situational needs of humans.

Examples of these categories are listed in Table 2. A simple example of compensating a human sense is prescription glasses one wears to maintain vision: The technology, the glasses, compensate for a decreased human sense, the vision. In a technically more complex example, Shull and Damian (2015) have reviewed the use of haptic wearables for sensory augmentation of partial sensory impairment, a replacement for total impairment and training for no impairment, concluding that such wearables can improve many clinical applications, e.g., rehabilitation, vestibular loss, or vision loss. Another example of such a system is the prototype *SpiderSense* presented by Mateevitsi et al. (2013). Using several sensors and tactile actuators on the human body, SpiderSense uses the sensor modules to scan the surrounding environment for objects and alerts the user for objects closer to 60 feet.

Table 2: Examples for the Augmentation of Human Capabilities

Augmentation	Objective	Example capability	Example augmentations
Senses	Compensate	Vision	Glasses for minor impairments, Haptic actuators for loss of visual sense
	Amplify	Vision	Night-vision device in low-light conditions, Binoculars for view of distant objects
Action	Compensate	Movement impairment due to amputated limb	Prosthetic limb
	Amplify	Lifting of heavy items	Exoskeleton
Cognition	Compensate	Decreased cognitive ability due to surgery	Assistance for working memory
	Amplify	Scan environment	Glasses showing additional information about the environment via AR

Note. This Table gives an overview of examples for the compensation or enhancement of one human capability. For a more detailed discussion of these and further examples for human augmentation, see Raisamo et al. (2019, p. 8-11).

The field of HA is relevant for this thesis, as the prototype applying vibrotactile warnings can be categorized as a tool of augmented cognition. By using information from multiple sources in the environment (e.g., Geofencing, Proximity Sensors, RFID, Object Detection, Computer Vision), integration and processing of these data sources for a warning system that applies personalized vibrotactile warnings could augment a worker's awareness for surrounding hazards. Whereas other research focuses on different technical implementations of vibrotactile warnings (e.g., Baek & Choi, 2018; Holden & Ruff, 2001), this thesis focuses on applying VR to simulate and evaluate such systems by receiving input from objects in the Virtual Environment (VE) and alerting users by providing directional tactile warnings. VR is suitable for developing novel ideas for human augmentation and creating prototypes, as all events and objects inside VEs are controllable, thus allowing to simulate complex systems, even (yet) non-existing ones (Sadeghian & Hassenzahl, 2021).

2.1.6 Summary

This section has introduced relevant concepts from cognitive psychology and human factors regarding human information processing. Understanding these processes is highly relevant for this thesis, as vibrotactile warnings will be examined under workload. In summary, the most important aspects are:

- The tactile sensory channel can be used as an information channel to convey hazard warnings.
- Humans have individual perceptual abilities. Thus, these subjective perceptions should be considered in the examination of vibrotactile warnings, as vibrotactile perception might differ among humans.
- The C-HIP model indicates that warnings have to be noticed by recipients and attract their attention. Although the model was created for visual warnings, the process can be applied to tactile warnings.
- Measurement of mental workload allows to examine if there are differences in between real conditions and VR. Additionally, the measurement also allows to investigate if and how controller interaction and locomotion techniques impact mental workload.

2.2 Tactile Feedback and Wearables

This section refers to technical solutions incorporating tactile or vibrotactile feedback. In 1997, the Japanese game console manufacturer *Nintendo* released an add-on for their controllers of the Nintendo 64 console, the *Rumble Pak*, which added force feedback to the controllers. Other manufacturers followed Nintendo and also integrated force feedback. Nowadays, vibrotactile feedback is found in everyday devices like mobile phones, and other wearable or handheld devices.

This section reviews the design and application of various tactile feedback mechanisms to understand factors to consider when designing wearables that produce tactile feedback. First, an overview of the different tactile actuators is given before focusing on vibrotactile feedback and referring to its use for different HCI contexts. The following aspects are relevant:

- Defining (vibro-)tactile feedback and differentiating it to haptic feedback.
- Understanding devices used to generate vibrotactile feedback.
- Factors that influence tactile perception.
- Parameters to configure vibrotactile feedback.
- Understanding its applications in HCI contexts.

2.2.1 Touch, Haptics, Tactile: An Explanation of Terms

Tactile feedback can be found in many everyday devices. For instance, smartphones are equipped with vibrotactile actuators for notification purposes (Oakley & Park, 2008), or game controllers try to increase the immersive experience for players by using vibrotactile feedback whenever in-game collisions occur or events like firing weapons happen (Hoggan & Brewster, 2012, p. 212). However, the use and the definition of terms referring to tactile feedback are not always precise or cannot be precisely defined in some cases (cf. Grunwald, 2001). For example, in some definitions, the term *haptic* is used as a classification of active exploration of humans or their movements, whereas tactile perception is classified as "passive touch" or sensations of skin that occur without an "active execution of movements" (Carter & Fourney, 2005; Grunwald, 2009; Grunwald & Beyer, 2001, p. 9f.). Another example refers to *haptic perception* as "knowledge of the world that is derived from receptors in the skin […] usually involving *active exploration*" (Wolfe et al., 2018, p. 446). Other definitions "limit the use of tactile to mechanical stimulation of the skin" (van Erp et al., 2010, p. 354). For example, Wolfe et al. (2018) define *tactile* as "the result of mechanical interactions with the skin" (p. 420). Therefore, a literature query for 'tactile' can result in a document set of research papers covering haptic feedback, tactile notifications, haptic interface design, vibrotactile navigation systems, or tactile displays. For the further course of this dissertation, this section introduces and defines essential terms related to haptic and tactile feedback.

The International Organization for Standardization (ISO) defines haptic as an 'umbrella term' with several subcategories (Hoggan & Brewster, 2012, p. 216). Following this definition, haptic refers to "sensory and/or motor activity based in the skin, muscles, joints and tendons" (ISO, 2017). In this definition, haptic feedback is classified into the categories of *touch* and *kinaesthesis* (see Figure 2.8). Kinaesthesis (or kinesthesis, kinesthesia) refers to the "perception of the position and movement of our limbs in space", and *proprioception* as the "perception mediated by kinesthetic and internal receptors" (Wolfe et al., 2018, p. 420). In other words, proprioception is needed to sense the own body position and movement, whereas kinaesthesis is needed to sense the activity of muscles, joints, and tendons (cf. ISO, 2017; Van Erp et al., 2006). *Touch,* on the other side, refers to "sense based on receptors in the skin" (ISO, 2017).

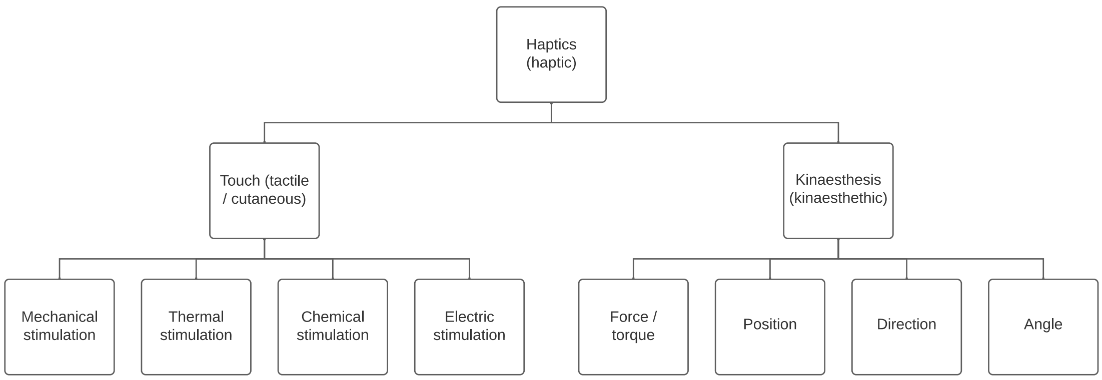

Figure 2.8: Definitions of haptic terminology, as proposed in ISO: Ergonomics (ISO, 2017)

When tactile feedback is used by mechanical stimulation, for example, by vibration or force, the feedback is applied using actuators that can be embedded in clothes or devices (Sharp et al., 2019, p. 231). If the mechanical stimulation of the skin is generated by vibration, it is called *vibrotactile feedback* (sometimes also written as vibro-tactile). *Vibrotactile displays* are, in general, arrays of vibrating modules or elements that are attached to the skin (Van Erp & van Veen, 2001). Other types of haptic feedback include skin sensations due to temperature, pain, stretch, or pressure (Pfeiffer & Rohs, 2017, p. 106). The term *force feedback* (or *haptic force feedback*) refers to feedback based on the resistance of virtual or remote objects (cf. Sallnäs et al., 2000).

2.2.2 Factors for Decreased Tactile Perception

The perception of tactile sensation can differ under certain activities. For example, the phenomenon of *tactile suppression* is known as the reduction of tactile perception during movement. It is considered to suppress or *gate* sensation in goal-directed movement (Juravle et al., 2017). Another phenomenon that is related to decreased tactile sensitivity is *inattentional numbness*. Murphy and Dalton (2016) have demonstrated a decreased awareness of tactile stimuli when attention is focused on something else.

In a study presented by Karuei et al. (2011), 13 body locations using five different vibration intensities were compared in two experiments. The researchers tested different locations for vibrotactile feedback: foot, thigh, wrist, stomach, upper arm, chest, and spine. According to the results, the detection rate was higher for the wrist and spine, although for the reaction time, the location did not matter. Vibration signals with an increased intensity were being detected faster, thus reducing reaction times compared to vibration signals with a lower intensity. However, movement did significantly reduce the odds of detecting vibrations and increased reaction times even to high vibration intensities. Visual workload did also significantly increase reaction times and decreased detection.

Gomes et al. (2020) studied the effect of physical movement, cue complexity, and body location on tactile change detection. They used a vibrotactile stimulus while participants were sitting, standing, or walking and used different cue complexities, for example, a vibration with increasing or decreasing intensity or a change in location, among others. The results have shown that the change detection accuracy was lower while standing or walking, compared to sitting. Furthermore, change detection accuracy decreases with increasing tactile cue complexity (Betza et al., 2017; Gomes et al., 2020).

In a study by Oakley and Park (2008), the authors used three different distractor tasks: text transcription, data entry, and walking. Their results have shown that performance to detect vibrotactile cues decreased in all conditions in which participants were doing a distractor task.

Research has shown that overall tactile perception can be manipulated by distraction. This effect has also been of research interest in the health care domain to reduce pain sensation. For instance, Lier et al. (2018) used VR to distract the tactile perception of 50 study participants. In their study, participants did a control condition, which showed a black screen, a passive condition, in which participants were exposed to a virtual environment, or an active condition, in which participants were exposed to the same environment but had to use a VR controller to shoot balls on targets, in a randomized order. The results have shown that the active VR experience had the largest effect on increasing the tactile perception threshold, thus decreasing tactile perception.

In summary, both physical movements, distracting tasks, and visual workload influence the detection and change detection of vibrotactile feedback. The literature has also shown that physical movement and visual workload increases reaction times to vibrotactile feedback. Thus, these aspects have to be considered in the evaluation of vibrotactile warnings in VR. In VR, users usually using controllers move around in the virtual world using VR controllers, thus limiting physical movements by normally standing or sitting on the spot.

2.2.3 Wearable Prototyping with Tactile Actuators

There exist several ways to create and utilize tactile feedback. This involves the use of *actuators* that are built into clothes or devices. Clothes or pieces of textiles that use actuators and sensors, for example, by sensing some stimulations from their environmental context and offering some functionality to users, are called *smart textiles* (cf. Schneegass & Amft, 2017, p. 4). Wearables, or wearable computing, refers to computing devices that users can wear. For the design of wearables, Gemperle et al. (1998) have provided guidelines that should be considered for *wearability*, "the physical shape of wearables and their active relationship with the human form" (p. 1). Although 13 guidelines are provided, the authors state that only the first six guidelines are generalizable (cf. p. 2):

1) Placement on the body
2) Form language, defining the shape
3) Human movement considering dynamic structures
4) Proxemics, human perception of space
5) Sizing for body size diversity
6) Attachment and fixing to the body

The placement guideline refers to designing for unobtrusive placement, for instance, areas that have low movement or are relatively the same size across adults. Humanistic form language refers to ensuring that the wearable offers a stable and comfortable fit, whereas human movement refers to considering all sorts of human movement in the design of a wearable. Size variation refers to designing wearables to fit individual body sizes. Lastly, attachment refers to creating forms that wrap around the body, rather than using single point fastening systems (Gemperle et al., 1998). According to their study, the most unobtrusive body areas for wearable objects are:

- The collar area,
- Rear of the upper arm,
- Forearm,
- Rear, side, and front ribcage,
- Waist and hips,
- Thigh,
- Shin, and
- Top of the foot.

Designing a wearable that produces tactile feedback requires some sort of actuator. Several different kinds of tactile actuators exist, for example, piezoelectric benders, air puffs, or electrodes. However, the probably most common way to apply tactile feedback is by using vibration motors. Two methods are used to create vibrations: either the vibration is a result of a moving coil or of a DC motor that uses an eccentric weight (cf.

Van Erp, 2002), also known as *Eccentric Rotation Mass* (ERM) vibration motors. ERM vibration motors are commonly used in mobile phones or other handheld devices, as they are small and inexpensive. Examples of different ERM vibration motors are shown in Figure 2.9.

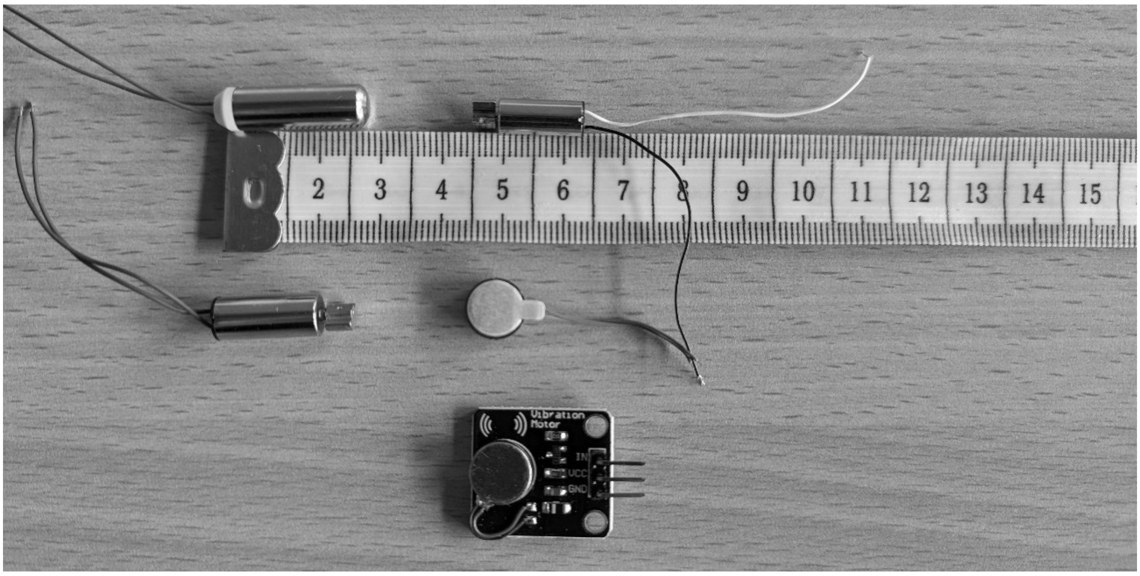

Figure 2.9: Examples of five vibration Motors

Note. Scale shows cm. Two types of vibration motors are shown: cylindric and coin motors. Encapsulated cylindric motor (top left), cylindric motors (top right and bottom left), pancake/coin vibration motor (bottom right), and coin vibration motor attached to a board (bottom right).

Such ERM vibration motors require a certain amount of power and current to rotate the mass. The number of rotations during a time period of one second is defined as frequency (in Hertz, Hz). For example, the coreless motor (Figure 2.9, right) weighs 20 grams, has a length of 21.7mm and a diameter of 7mm, needs a rated voltage of 3.0V, and generates a maximum frequency of 125 Hz (7.500 RPM, whereas RPM stands for *Revolution per minute*). The generated vibration frequency increases with increasing operating voltage (e.g., L. A. Jones et al., 2004). Measurements of vibrations can be achieved by using accelerometers, sensors that allow measurement of acceleration.

Due to their small size, such vibration motors fit into mobile devices or wearables and can therefore be used for a variety of applications. As examples of different wearable devices, researchers have integrated vibrotactile feedback into a torso belt (van Erp, 2005, 2008), presented vibrotactile feedback via a wearable armband (Cobus et al., 2018), a vest (L. A. Jones et al., 2004), the wrist (S. Lee & Starner, 2010), or in HMDs (Kangas et al., 2017). Cinaz et al. (2011) have used vibration in a wristband for a vibrotactile reaction time task, allowing them to do reaction time tests in mobile settings.

However, there are other techniques to create tactile feedback. Stratmann et al. (2018) presented the use of pneumatic cues by positioning two airbags at the back of the shoulder of participants for navigational cues. The airbags allowed shape-changing by applying pressure. In a lab study, the researchers evaluated their system ('ShoulderTap') with twelve participants and compared it to vibrotactile cues on shoulders. The results showed that the subjectively felt ‘urgency’ of cues was rated significantly higher for vibrational cues than pressure-based cues (Stratmann et al., 2018, p. 4). Another example, using pressure feedback, has been shown in a prototype of a handheld controller by Chen et al. (2019). In their prototype, a three-by-five-pin array is embedded in a custom controller that allows using directional pressure in eight cardinal directions. It has been used and tested in two games to provide direction information of enemy projectiles and to present users with haptic feedback of in-game rain (D. K. Y. Chen et al., 2019). Hamdan et al. (2019) presented a prototype called *Springlets* that allows non-vibrating mechanotactile feedback. Springlets are thin and lightweight ‘plasters’ that can be applied on the skin and use shape memory alloy springs. By using on-skin stickers, Springlets are attached directly to the skin and can be worn on various body parts (Hamdan et al., 2019).

In summary, for the studies in the thesis, a wearable device will be designed that follows the presented guidelines on wearability, that has to fit different body sizes and be unobtrusive to participants’ movements. ERM vibration motors will be used, as they can be easily integrated into a wearable prototype due to their small size.

2.2.4 Vibrotactile Parameters and Guidelines

Vibrotactile feedback can be configured by several parameters. For instance, a smartphone notification that should be one second long could be designed by using one continuous vibration for the whole second, or it could be designed by using a pattern of reoccurring vibration-pause periods, as shown in Figure 2.10. Depending on how a vibrotactile signal is designed, it can be (subjectively) perceived differently, for example, according to its perceived urgency or annoyance (Saket et al., 2013).

However, the perception of vibration strength can be affected by the size of the vibration motor or the surrounding device. For example, Yao et al. (2010) have shown that vibrations with the same acceleration are perceived to vibrate with greater strength in heavier boxes than in lighter ones, indicating that with larger weights, less acceleration is needed to produce a similar perceived strength. Additionally, the researchers have shown that the strength of vibrations with a higher driving frequency is perceived as weaker than vibrations with lower frequencies (p. 58). Such results are of importance for design of vibrotactile feedback and for testing vibrotactile variations within a design study. As another example, Hoggan et al. (2009) evaluated audio and tactile feedback for a typing task on a mobile device in a noisy and vibrating environment. Their results have shown a decreasing performance for audio feedback at environmental noise levels of 94 dB and for tactile feedback at environmental vibration levels of 9.18 g/s. The authors argue that at these levels, the feedback should be presented by another modality (cf. Hoggan et al., 2009).

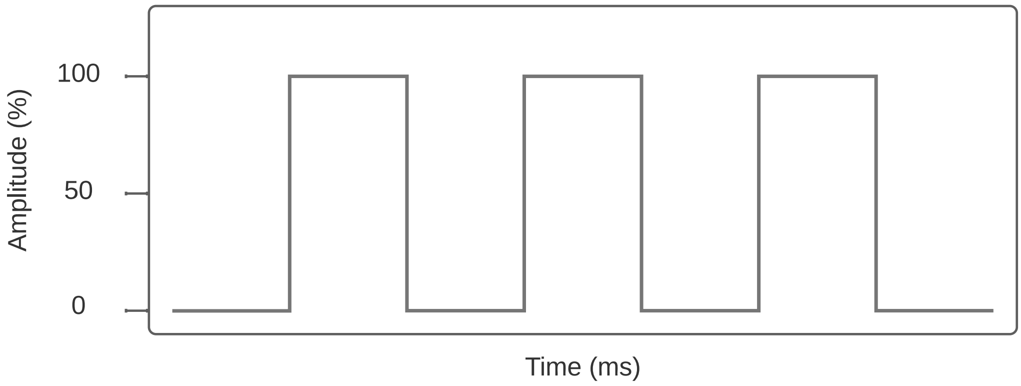

Figure 2.10: Example of a Vibration Pattern

Note. In this example, the vibration signal repeats three times for the same time span with an amplitude of 100%. The duration of the signals has the same time length as the pauses in between.

Depending on the complexity of the to-deliver message, researchers have provided guidelines that should be considered when using vibrotactile feedback. Van Erp (2002) proposed guidelines that considered four primary parameters when applying vibrotactile stimuli: amplitude, frequency, timing, and vibration location. For the design of vibrotactile feedback, these parameters have to be considered to ensure stimulus detection, allow information coding, incorporate comfort in the design, and avoid pitfalls. Vibration stimuli can be successfully detected when the amplitude of the vibration exceeds a certain threshold. This threshold is "dependent on several parameters, including the frequency […] and the location on the body" (Van Erp, 2002). Regarding the information coding, stimuli can be configured by a *subjective magnitude*, meaning different levels of felt vibration intensity, frequency, temporal patterns, or by location. Guidelines on comfort refer to an unobtrusive and comfortable design of tactile displays, as they are worn for long periods of time, and possible injuries due to heat generation should be ruled out. Additionally, tactile stimuli with high intensities "may lead to discomfort" (Van Erp, 2002, Section 2.3). Finally, van Erp describes pitfalls that should be avoided. The pitfalls include spatial effects, like spatial masking of stimuli by other stimuli; temporal effects, like presenting multiple stimuli simultaneously; or spatiotemporal interactions, where time and space of stimuli can result in a new percept, like a perception of motion. Regarding the temporal effects, the author distinguishes between *temporal enhancement*, a result of presenting multiple stimuli in the same frequency band, and *temporal masking*, referring to the masking of one stimulus by another when they are located near each other.

Brewster and Brown (2004) have presented the concept of *Tactons*, which are, compared to binary alerts, defined as structured tactile messages for non-visual, tactile displays. A *tactile display* refers to systems that transfer information using the sense of touch instead of audio-visual senses. In their work, they have researched multiple parameters that should be considered when designing tactons:

- **Frequency**: The skin's maximum sensitivity is around 250Hz and no more than nine different frequency levels should be used.
- **Amplitude**: No more than four different intensities should be used.
- **Waveform**: Differentiation between sine waves and square waves is possible.
- **Duration**: Presentation of vibration pulses with different durations.
- **Rhythm**: By building groups of different durations that can be composed into "rhythmic units".
- **Body location**: Information can be positioned across the body, incorporating the fact that different body locations can "have different levels of sensitivity and spatial acuity" (Brewster & Brown, 2004).

In later work, Brown et al. (2006) refer to the parameter "roughness" as using amplitude-modulated waveforms. These signals are created by multiplying signals of a specific sine wave of a given frequency by a sine wave of another frequency, creating the possibility of applying "rough" stimuli (Brown et al., 2006).

Carter and Fourney (2005) proposed tactile and haptic interaction guidelines based on the inputs/outputs, the encoding of information, content-specific encoding, user-individualized tactile and haptic interfaces, and interaction tasks. As an information encoding example, the guidelines propose that tactile messages should be self-explaining to the user. An example of tactile outputs proposes that "haptic output" should seamlessly integrate into the user's task (Carter & Fourney, 2005, pp. 86–90).

Regarding the perceived urgency of vibration-based notifications for mobile phones, Saket et al. (2013) evaluated ten different vibration patterns. The researchers identified three factors that contribute to users' perceived urgency of vibrotactile alerts: the gap length between vibrations, the number of gaps during an alarm, and the length of the vibration itself. According to their results, vibration patterns designed for urgency should be held simple, with the least number of gaps.

In summary, the guidelines presented by van Erp (2002) overlap with the guidelines for wearability by Gemperle et al. (1998) highlighting the importance of an unobtrusive design. Guidelines on vibrotactile feedback have shown five parameters to consider when designing vibrotactile feedback: frequency, amplitude/intensity, waveform, the 'rhythm' (duration of vibration pulses and pause between vibrations), and body placement/location. The literature also provides guidance on the design of vibrotactile feedback for particularly urgent messages (such as necessary for hazard warnings). Here, the recommendation is to use simple rather than complex vibrotactile patterns.

2.2.5 Example Applications of Tactile Feedback

The tactile channel is getting more and more attention in research. Examples can be found in the research of cross-modal interaction, e.g., to represent information via multiple senses, or in multi-modal interaction devices, e.g., that use the tactile channel for increasing immersion while playing a game. Nowadays, the applications for tactile feedback seem endless, as the tactile modality is seen as "being nearly as efficient and omnidirectional as the auditory modality in capturing attention" (Wickens & McCarley, 2008, p. 32). This section provides an overview of different applications for tactile feedback, underlining the relevance of research and showing the potential of utilizing the tactile sense.

Application areas vary according to their objective, e.g., to substitute another sense with the tactile sense, to use the tactile sense as an additional information channel, or to fundamentally understand how the tactile channel can be utilized. As an example of the latter objective, Ju et al. (2021) have investigated whether prior recorded vibrotactile emotions can be recognized by others. In their study, participants expressed four emotions (joy, anger, sadness, and relaxation) in vibrational patterns during a first session. Then, in a second session, the participants had to recognize emotions by interpreting the vibrations. The results have shown that the accuracy of recognizing the correct emotion of other participants' vibrations was between 40.5% - 73.8% (Ju et al., 2021).

An example of utilizing the tactile sense to provide additional information has been presented by Teng et al. (2021) to increase haptic feedback from virtual objects in Mixed Reality (MR) environments. They used a foldable haptic actuator that allowed participants to feel pressure and vibrations, for instance, when touching a virtual button. It is attached to the top of a user's fingernail, leaving the finger pad free until the prototype recognizes the touch of a digital object, unfolds to the finger pad, and applies pressure to it (Teng et al., 2021). Knierim et al. (2017) have presented an example of tactile feedback in VR by using tracked mini-quadcopters to mock virtual objects in the scene. The quadcopter's orientation in space was used inside the VR scene to simulate bumblebees, arrows, and other objects that could hit the user.

An example of cross-modal interaction can be found in research on human augmentation for sensory substitution. For instance, systems can process environmental data that a human cannot perceive due to an impairment and translate the data input into stimuli for another human sense. Examples of systems are tactile vision substitution or tactile audio substitution (Hoggan & Brewster, 2012, p. 225).

The following sub-sections give examples where tactile feedback is used as a substitute channel to reduce cognitive demands of the visual or auditory system, to augment the users, or to augment the user's perception possibilities. The sections are not categorized according to their objective to utilize the tactile sense. Instead, the sections provide example applications frequently recurring during literature searches and scanning.

2.2.5.1 Vibrotactile Navigation Systems

Vibrotactile feedback has been used in many studies for navigation tasks. While driving vehicles, humans require their auditory and visual channels for navigating through traffic or the environment, whereas navigational information could also be transferred via the tactile channel to prevent looking at a visual screen for directions (e.g., Escobar Alarcon & Ferrise, 2017). For example, Kiss et al. (2018) presented the prototype 'MOVING' (Motorbike Vibrational Navigation Guidance) to explore how tactile feedback could be used as motorbike navigation system. The authors first applied an on-body vibration measurement of the motorbikes' vibration to the motorcyclist and used, based on the results of the measurement, a kidney belt to attach the vibration motors around the participant's waist/torso. For their design, they used two 2x3 matrices of vibration motors located on the left and right back of participants' waists and used multiple vibration designs, whereas, depending on the call-to-action, vibration impulses lasted between 300ms-1700ms with pauses of 75ms or 500ms in-between. The authors evaluated their vibrotactile navigation system in a real-world situation on a pre-defined route. Results have shown that participants made significantly fewer errors than with a visual navigation system.

Other examples of vibration-based navigation research include pedestrian navigation (Heuten et al., 2008), cycling (Escobar Alarcon & Ferrise, 2017; Matviienko et al., 2019; Pielot et al., 2012, 2012), vehicle driving (Di Campli San Vito et al., 2019; Van Erp & van Veen, 2001) or even skiing (Aggravi et al., 2016). As an example of pedestrian navigation, Heuten et al. (2008) have demonstrated the *Tactile Wayfinder*, a spatial tactile display prototype in the form of a vibrotactile belt worn around the hips. The prototype integrates six vibration motors equally distributed around the belt at a distance of 60°. To display directions between two motors, the intensity of the motors was reduced. For example, to direct for 60°, the motor at 30° and the one at 90° were activated with an intensity of 50%. The evaluation results have shown that participants were able to recognize and understand the indicated directions given by the belt and stayed inside a corridor of a pre-defined route on an open field. A review of vibrotactile navigation systems found that the most prominent location for the vibrotactile displays is the waist, followed by the wrist, back, hand, thigh, and foot (Krauß et al., 2020).

In summary, the presented examples for vibrotactile navigation systems have shown that directional vibration signals are generally understood by participants, even when even when ambient vibrations occur, as on motorcycles. However, vibration signals in navigation and warning systems differ in their meaning: while vibrations for navigation indicate the direction in which the user should move, vibrations for warnings indicate the direction of a hazard that should be avoided.

2.2.5.2 Vibrotactile Collision Warning Systems

Another application for vibrotactile feedback systems are collision warning systems to increase human safety. For instance, in the context of cycling, Vo et al. (2021) have presented the collision warning prototype *TactiHelm*. It is a bicycle helmet that provides that uses four tactile actuators inside the helmet for each cardinal direction, informing the user via their heads' skin. The authors used two vibration patterns: a single vibration of 500ms alerting users of vehicles that were at a far distance and two vibrations of two 200ms with a 200ms pause to warn of vehicles at a close distance. A user study with seven participants revealed that the accuracy in identifying the proximity was 91%, whereas identifying the correct direction of a vibration was 85%. The evaluation was done on cycling tracks and open gravel roads free of obstacles, traffic, or pedestrians. In this setting, the study facilitator used a mobile phone that was connected to the helmet, allowing to evaluate the system in the open (Vo et al., 2021).

A similar use case for vibrotactile collision warnings has also been explored more intensively in the automotive sector. As vision is considered to be the primary sensory channel for driver information processing (Shinar & Schieber, 1991), there are many examples in the literature where vibrotactile feedback has been used to inform drivers via the seat, the waist, the seatbelt, or the steering wheel (Chun et al., 2013; Ho et al., 2006; Meng et al., 2015; Morrell & Wasilewski, 2010). For instance, Ho et al. (2006) investigated the effectiveness of vibrotactile warning signals in preventing front-to-rear-end collisions in driving simulators. In their study, eleven participants used a driving simulator in which they followed a lead car at a safe distance. The brake lights of the lead car were disabled, and participants had to respond as quickly as possible to the deceleration of the lead car. At the same time, they received either vibrotactile warnings or no vibrotactile warnings. In their results, the authors describe that participants had a significantly faster braking response and larger safety margins to the lead car when they received a vibrotactile warning signal (Ho et al., 2006). In a follow-up study, Ho et al. (2007) compared unimodal auditory or vibrotactile cues with a combination of audio-tactile cues for front-to-rear-end collisions in a driving simulator. The results have shown that the multisensory warning signals led to a significantly faster braking response than the unimodal signals.

In summary, the examples have shown that the tactile channel has the potential to be used for warnings when people perform visually demanding tasks. Depending on the context, visual and auditory senses are usually necessary for task performance, whereas the tactile sense is not. Then, the example of TactiHelm has shown how such systems can be evaluated in a non-lab setting by using mobile equipment and wireless interfaces, which might be relevant for evaluations outside of VR Labs.

2.2.5.3 Vibrotactile Proximity Warnings Systems

The last example application is *Proximity Warning Systems* (PWS), which are very closely related to collision warning systems of the previous section. Such systems are researched to improve worker safety with technological advancements like sensors, cameras, and others, enabling the detection of real-time safety issues and delivering real-time warning messages.

For instance, Schultheis et al. (2012) evaluated such a system around railroad tracks using Peltier elements, vibration motors, and earbone conduction as warning devices. From their pilot studies, the authors concluded that for the Peltier elements, only cold stimuli were perceived, while heat stimuli often went undetected. The prototypes with vibrations were well perceived at the waist and abdominal area and were rated as unobtrusive. Earbone conduction was also rated as a promising approach, as participants were able distinguish three test signals (alarm, warning, and system error). In a follow-up work to evaluate a prototype of a wrist display, glasses using LEDs, and a bone conduction system, Schultheis (2015) presented design recommendations and challenges in designing laboratory studies to evaluate such prototypes for safety-critical areas. In the first study, the participants sat while constructing a model from building blocks according to the instructions. In the second setting, participants built a 1.7m high wooden hut. Schultheis concluded how difficult it is to find a cognitively demanding task with practicable working conditions to evaluate such prototypes and pointed out that further evaluations should be conducted in the field (Schultheis, 2015, pp. 137–138).

A further example of such systems is the research on real-time hazard perception of workers shown by Cho and Park (2018) with the development and evaluation of an embedded sensory system for worker safety by applying vibrotactile warnings. The authors attached cylindrical-shaped vibration motors to the back of a construction site vest. To communicate with the motors, they send signals wirelessly to a microcontroller. The evaluation of their prototype was done in two experiments. In the first experiment, five participants wore the vest and documented every signal they recognized on paper. The vibration signals changed in intensity, length, and delay between vibrations. In the second experiment, three of the five participants took part in an emulated hazard experiment. The hazards were simulated by throwing a ball at the participants. Before the ball was thrown, participants received a vibration signal to their back, indicating which action to take to avoid hazards (Cho & Park, 2018).

In a follow-up study, Sakhakarmi and Park (2019) examined potential design parameters to configure a tactile sensory system for communicating hazard information to construction workers. In this context, they examined three factors: the number of vibration motors needed to send information, the spatial distance between vibration sensors for high detection accuracy, and the arrangement of vibration motors to increase perception accuracy in distinguishing signals. Cylindrical vibration motors were used, which were triggered by a microcontroller. The motors had a rated voltage of 3.0 Volt and rotation speed of 12.000 +- 2500 RPM (Sakhakarmi & Park, 2019).

In summary, the examples revealed limitations when testing PWS in laboratory settings and the field. Thus, the central part of this dissertation thesis is located in the research gap of enabling researchers to evaluate such vibrotactile warning systems in VR simulations. Therefore, the use case of PWS is taken up and analyzed in greater detail in Section 3.1.4 to draw requirements for a VR environment from the use case and highlight this work's design space as this work combines research on vibrotactile warnings for collision avoidance and VR for construction site safety. The work aims to explore the use of such warning systems and evaluate them in a close-to-reality way via VR simulations for work safety. In doing so, the work explores the possibilities of VR simulations to close this missing link via accessible and lightweight testing of vibrotactile warnings.

2.2.6 Summary

To summarize all essential and relevant aspects from the section on tactile feedback and wearables for the further course of this thesis:

- A working definition of vibrotactile feedback was presented as mechanical stimulation of the skin, and it was distinguished from other forms of tactile feedback.
- It has been shown that factors such as visual workload or physical movements can increase reaction times to vibrotactile feedback. In addition, detection and change detection of vibrotactile feedback reduces with increasing workload, distracting tasks, and physical movement. Finally, it was also shown that in situations with a high visual workload (e.g., driving a car), the transmission of warnings via the tactile sensory channel offers much potential.
- Guidelines were presented for unobtrusive wearability. Examples of vibrotactile navigational systems have shown that, for directional feedback in all cardinal directions (and in-between), the chest and waist area are particularly suitable.
- Several types of vibration motors have been presented that are suitable for such research purposes as in this thesis. The motors can be controlled wirelessly via microcontrollers, allowing the evaluation of such systems in the open.
- The most important parameters for configuring vibration signals were presented: frequency, intensity, waveform, rhythm, and body placement. In addition, according to the literature, a simple vibration pattern should be used for warning purposes.
- Examples of PWS were presented in which the evaluations were primarily focused on the technical feasibility of the systems and participants had a low workload. Thus, the evaluations lacked real or close-to-reality test conditions, which are to be fabricated via VR in this thesis.

2.3 Virtual Reality

Virtual Reality (VR) allows humans to experience virtual scenes and environments in an immersive way. The term was proposed in the 1980s (see next subsection). However, VR is driven by the technological advancement of its hardware (cf. Dörner et al., 2019). Thus, VR has gained much attention in research and the industry since the release of the Oculus Rift in 2013. This evolution of VR hardware is sometimes referred to as the “second wave of VR” (cf. Anthes et al., 2016) or “new era of VR” (cf. Boletsis, 2017). Since then, advancements in VR have produced more performant, reliable, affordable, and comfortable VR hardware for the mass market.

In order to understand the possibilities and limitations of VR, this section starts by covering fundamental aspects of VR (2.3.1) before going into more detail about research with VR (2.3.2). The subsequent sections (2.3.3) will focus on research applications and VR laboratories.

2.3.1 Fundamentals of Virtual Reality

In 1957, Morton Heilig invented “Sensorama”, a mechanical machine that played prerecorded films which were displayed in color and used multi-modal feedback. He patented the machine in 1962, and described it as “Experience Theater” that “created an illusion of reality for a mass audience by filling all of every spectator's senses […] with color, visual motion, 3D, peripheral imagery, directional sound, aromas, and tactile sensations" (Heilig, 1998, p. 344). Although the system was not interactive, it is understood as a precursor for VR (Jerald, 2016, p. 21; Mandal, 2013).

For many researchers, the next decisive step for today's VR was made by Ivan Sutherland in the 1960s when he was working on a head-mounted display to project images into the surrounding environment (Sutherland, 1965, 1968). This example is understood nowadays as the first example of a working *Augmented Reality* (AR) system, a term that emerged in the 1990s (cf. Dörner et al., 2019, pp. 20, 26–27). During a phase beginning at the end of the 1980s, the first systems that can be understood as VR systems emerged, and the term 'Virtual Reality' was proposed (e.g., Lanier, 1988).

As a consequence of the historical developments, the label *VR* has been "frequently used in association with a variety of other environments, to which total immersion and complete synthesis do not necessarily pertain, but which fall somewhere along the virtuality continuum" (Milgram & Kishino, 1994, Section 1, para. 2). Based on the mix up between terms, Milgram and Kishino (1994) have proposed a taxonomic framework to classify *Mixed Reality* (MR) displays. Part of this framework is the Reality-Virtuality (RV) Continuum which allows us to distinguish MR visual displays depending on virtual and real aspects (Figure 2.11). On the far left of the continuum, the real environment refers to environments that consist solely of real objects. MR, between the real and virtual environments, refers to environments "in which real world and virtual world objects are presented together within a single display" (Milgram et al., 1995, p. 283). The further to the right on the continuum, the smaller the proportion of the real environment. AR refers to technologies that augment the real world with digital objects. Thus, AR allows users to see the world around them with "virtual objects superimposed upon or composited with the real world" (Azuma, 1997, p. 356). *Augmented Virtuality* (AV) refers to virtual environments that integrate real or physical objects into the environment, whereas *Virtual Environments* (VE) are defined as environments that consist solely of virtual objects. Thus, a VE is described as an artificial and digital world or a "computer-generated immersive environment that can simulate both real and imaginary worlds, often in three dimensions (3D)" (Stanney & Cohn, 2012, p. 644). VR lets users experience and immerse into virtual environments. This distinction between the different forms of mixed realities is important as this thesis examines VR as a method for studying vibrotactile warning systems and aspects of occupational safety in VEs.

Although the RV continuum served the field with captivating practicability, researchers have also discussed its limitations (e.g., Lindeman & Noma, 2007; Skarbez et al., 2021; Speicher et al., 2019). To give one example, Skarbez et al. (2021) argue that the scope of MR should include the right end of the continuum (VE), which they refer to as "*External Virtual Environments*". In their argumentation, the authors describe that with VR systems, the body's internal senses (vestibular and proprioceptive) would still be controlled by reality. Additionally, the authors argue that the RV continuum does not include a complete "Matrix-like" virtual environment, which would be fitting to VEs on the RV continuum. *Matrix* refers to the infamous science fiction action film series 'The Matrix' (released in 1999), in which humanity lives in a dystopian future and is cognitively encaptivated in a completely virtual world while their bodies are used as an energy source by intelligent machines. In the film, all human sensory sensations (inside the Matrix) result from direct brain stimulation. The authors argue that this "is the only type of virtual environment that could exist outside of the mixed reality spectrum" (Skarbez et al., 2021, p. 3), as with all other VR systems, users would "experience such external VEs as mixed reality, with virtual objects situated within a real environment" (p. 3). This aspect is relevant for the thesis, because with VR people can visually and auditorily explore other worlds, but hardly move from the spot in their real environment.

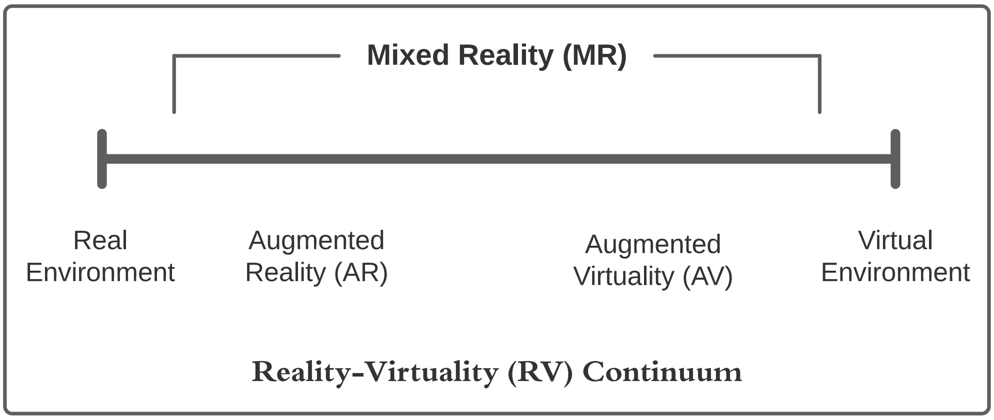

Figure 2.11: The Reality-Virtuality (RV) Continuum, adapted from Milgram et al. (1995)

For the further course of this dissertation, VR systems are generally understood as visual displays that allow experiencing artificial and virtual VEs. Head-worn VR displays (or VR headsets) refer to immersive *Head-Mounted Devices* (HMDs), which encapsulate a user's visual perception from reality into a synthetic VE. The following subsections discuss aspects of VR relevant to this thesis's topic.

2.3.1.1 Virtual Reality Hardware

VR systems usually consist of three main components: an interface displaying the VE to the user, tracking devices that translate head and body movements into the VE, and interaction devices allowing users to interact with objects in the VE (Stanney & Cohn, 2012). Besides HMD-based VR hardware, *Cave Automatic Virtual Environments* (CAVE) use projections on screens surrounding the user to display VEs. In contrast, HMDs isolate a user's vision from the (physical) environment and show the VE on a display inside the HMD (example in Figure 2.12). *Cardboard VR* uses smartphones that are inserted into a cardboard headset.

HMD-based VR systems usually consist of some visual headset to display the VE, controllers to interact inside the VE, and tracking devices to identify the position and orientation of limbs and the head inside the VE (e.g., Stanney & Cohn, 2012, p. 644). The freedom of movement inside a VE is defined as *Degrees of Freedom* (DoF). For example, three DoF are given if humans can rotate along the X, Y, and Z-axis (3-DoF). If translating along the X, Y, and Z-axis is possible, an additional three DoF, therefore six degrees of freedom, are possible (6-DoF).

Figure 2.12: HTC Vive Pro Eyetracking

HMD-based VR systems can differ in their components. For instance, systems like the HTC Vive Pro require a *lighthouse tracking system* to get the position of users in VR. Other systems, such as the Meta Quest 2 use inside-out tracking, meaning the HMD uses on-board sensors for tracking and does not need external tracking devices. HMDs also differ in their mobility, as the Meta Quest 2 is a standalone device, whereas the Vive Pro also depends on a high-end external computer. Newer conventional VR hardware is usually equipped with headphones.

2.3.1.2 Immersion and Presence

Several parameters can describe VR experiences, such as the degree of perceived realism, the perceived presence in the scene, or the degree of immersion. By separating oneself from the real world through immersive HMDs, one can be psychologically and mentally in other places (Stanney & Cohn, 2012). That engagement within VEs that connect with humans on a psychological level with the virtual experience is called *immersion* (Murray, 2020).

To distinguish between immersion and presence, Slater (2003) referred to immersion as the technological capabilities of VR systems that allow to experience a VE. In contrast, presence is seen as a response to the given experience and the extent of involvement or as “the subjective experience of being in one place or environment, even when one is physically situated in another” (Witmer & Singer, 1998, p. 225). Mestre and Vercher (2011) concluded that immersion should describe the objective characteristics of VR devices, whereas presence should be noted as the subjective effect that immersion produces. Thus, presence could be understood as the subjective response to the immersive experience.

Regarding presence, Witmer and Singer (1998) argued that for experiencing presence, *involvement* and *immersion* are necessary. Involvement refers to a “psychological state experienced as a consequence of focusing one’s energy and attention on a coherent set of stimuli or meaningfully related activities and events” (p. 227). In their view, immersion is defined as a “psychological state characterized by perceiving oneself to be enveloped by, included in, and interaction with an environment” (p. 227). Presence can be supported or enhanced by perceptual features (e.g., realism, interactivity), content characteristics, or interpersonal, social context (Stanney & Cohn, 2012).

Mestre and Vercher (2011) noted that immersion and presence should not be mixed up with the term *realism.* They named two problematic aspects of the term realism. On the one hand, the authors argue that the goal should not be to create a VE that is a copy of reality. On the other hand, it is possible for VEs to contain content (places, creatures) that do not exist in reality (cf. Mestre & Vercher, 2011). However, the degree of realism of the virtual environment and the objects inside might influence the subjectively perceived presence, as shown in a study by Hvass et al. (2017). Other studies did not support this finding, as the degree of (visual) realism did not affect presence (van Gisbergen et al., 2019).

Slater (2009) argued that presence (in the sense of “being there”) consists of two illusions: (1) *Place illusion* as the illusion of being in the place that VR depicts and (2) *plausibility illusion* as the illusion that the virtual scenarios are occurring. The author concluded that when both illusions occur, participants would respond realistically to the happenings in VR (Slater, 2009; Slater et al., 2022). In the same direction, Weber et al. (2021) added to the discussion on presence that instead of relying solely on presence in the sense of “being there”, presence should also be measured in the sense of *perceived realism* of VEs. According to the authors, perceived realism is the result of “(1) the subjective degree of reality of the depicted environment and (2) its overall plausibility and credibility” (p. 1).

The concepts of immersion and presence are highly relevant for this thesis since VR, as a method, must enable realistic depictions of real-world scenarios to elicit people's most realistic actions and reactions. Thus, to get the close-to-reality actions of participants, it is essential to understand how they subjectively perceive the VEs and the overall happenings in the VEs.

A common method to assess presence is the use of questionnaires. Examples of such questionnaires can be found in the *Presence Questionnaire* by Witmer and Singer (1998) or in the *igroup Presence Questionnaire* (iPQ) by Schubert et al. (2001). The iPQ uses a 7-point Likert scale (strongly disagree to strongly agree) and includes 14 items to measure the experienced spatial presence (SP, five items), the involvement in the scene (INV, four items), the experienced realism (REAL, three items) and one additional item to assess the general sense of being in place (GP).

Schwind et al. (2019) evaluated the use of presence questionnaires *in* VR by comparing two presence questionnaires for two different levels of immersion. Depending on the condition, participants filled out the questionnaires inside the VR scene or on a computer. Their results indicate that the condition had no effect on the measured presence. Filling out presence questionnaires in VR also reduced the overall duration of their study and reduced the disorientation felt by participants. However, using questionnaires in VR extends the time participants are exposed to VR, which in turn can lead to the onset of health-related issues.

2.3.1.3 Health and Safety Aspects

A significant challenge regarding perception in VR is *motion sickness*, a sickness with common symptoms such as nausea, vomiting, headache, dizziness, and others, which is caused by sensory conflicts between visual and vestibular stimuli (Goldberg, 2012, p. 12). Some authors referred to sickness triggered by simulations with the term *Cybersickness* (Hale & Stanney, 2015, p. 534).

While in VR, the human visual system detects moving objects and the own movement in the scene, although the user is usually standing or sitting stationary during the experience. This mismatch of sensory information between the visual and vestibular system can lead to motion sickness symptoms in VR, sometimes explicitly referred to as *VR sickness* (Clay et al., 2019; Murray, 2020). A straightforward solution to avoid or minimize motion sickness in VR is to design the virtual environment in a way that the user or player does not have to use continuous movement but rather use teleportation to move around in the environment. However, using teleportation as a locomotion technique in VR has several downsides. For example, teleportation reduces user's presence due to unrealistic movements around the scene (Prithul et al., 2021). Specifically for research, this unrealistic way of moving through a virtual world might not be suitable for many research questions in which a more natural way of moving around is needed, for instance when eye tracking is relevant in the VR scene (Clay et al., 2019, p. 4). Depending on the specific research question and actual use case, other locomotion techniques could be considered (cf. following section 2.3.1.4). To assess motion sickness, researchers use monitoring vivid data or subjective questionnaires, such as the *Simulator Sickness Questionnaire* (Kennedy et al., 1993).

Another relevant safety aspect is the visual (and auditory) isolation of VR users from their natural environment, increasing the risk of hitting near objects or loosing balance. For example, Jones-Dellaportas et al. (2022) describe a case in which a 58 year old man injured himself while using VR. While falling, he reportedly did not break his fall with his hands and "fell into a bannister and then the floor, hitting his head on a plug socket". In another medical case report, a VR fall of a 57-year-old man resulted in a spinal cord injury, hypoglossal nerve injury, vertebral artery dissection and traumatic brain injury.

The man reportedly could only remember snippets of the incident and recalled that he was standing up in VR when a "forward-free-falling scene was presented to him visually" (Warner & Teo, 2021, p. 1). In this similar case, the man also did not use his hands to break his fall. He lost consciousness for 5 minutes after he hit his forehead on a bannister before falling face down on the floor (pp. 1-2).

According to recent news, insuring companies have seen a rise in insurance claims from VR users due to an increasing number of accidents while using VR (Bartholomew, 2022). Cucher et al. (2023) have analyzed injury data concerning VR hardware from the National Electronic Injury Surveillance System (NEISS) for the U.S. In their results, the authors describe an increase of VR-related injuries by 352% between 2017 and 2021. Dao et al. (2021) have presented an analysis of 233 VR fail videos obtained from the video platform *YouTube*[2]. They defined strong disruptions of VR experiences as *breakdowns* and categorized the findings according to 1) types of fails, 2) causes of fails, 3) spectator interaction. According to their results, the main type of fails was an *excessive reaction* of VR users (53% of clips) and the main causes were *fear*, *sensori-motor mismatch*, and *obstacles in the real world* (Dao et al., 2021).

In summary, the health and safety aspects of VR use are relevant for conducting studies with VR. On the one hand, attention should be paid to whether motion sickness can occur in participants, on the other hand, the safety of the participants must be ensured all time.

2.3.1.4 Interaction and Locomotion

Interaction in VR is different compared to other types of computing devices. Rekimoto and Nagao (1995) have discussed styles of HCI for different technologies (Figure 2.13). For example, with conventional personal computers (PCs), a gap exists between interactions with the computer and interactions with the real world (a). To overcome this gap, a user could, for example, print out a document from the PC. However, markings on the printed version will have no effect on the digital document on the PC. In VR (b), the user interacts with the virtual world, but the actions inside VR should have no influence on the real world. With ubiquitous computers (c), users can interact with the computers which exist in the real world but also with the real world itself. Augmented Reality (d) allows users to interact with the real world and supports the interaction with augmentation.

To interact with a VE, users need some interaction devices. Conventional VR headsets include a pair of controllers, which are usually equipped with a joystick or trackpad and several buttons. Such controllers also allow haptic feedback by using vibrations when, for instance, the user picks up or hits a virtual object. Besides controller-based setups, newer systems allow hand tracking or finger tracking.

[2] Youtube.com

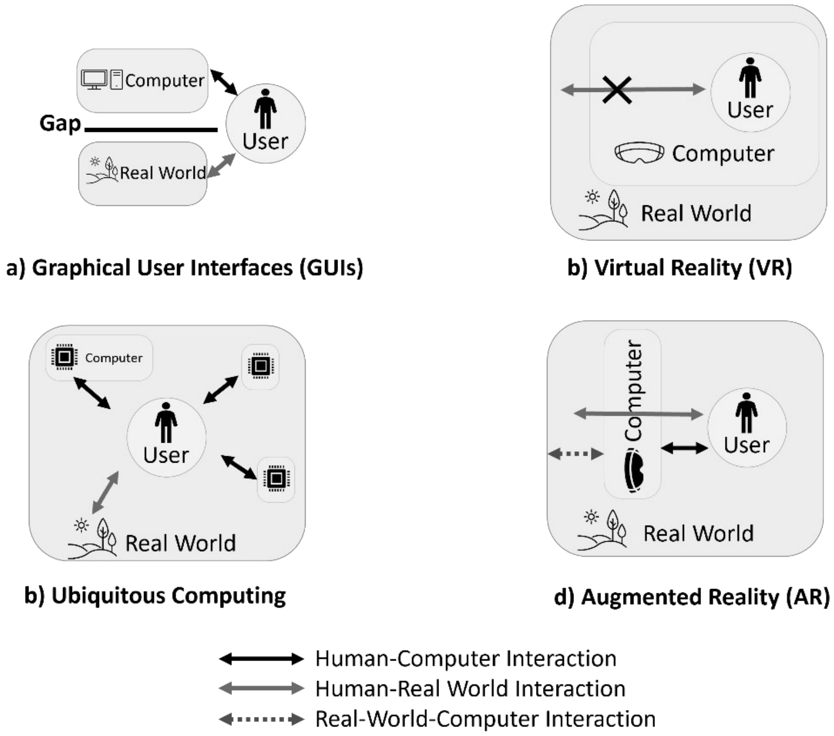

Figure 2.13: Comparison of HCI styles (adapted from Rekimoto & Nagao, 1995, p. 2)

In addition to interacting with virtual objects, moving around in the VE is also a challenge in VR. A simple way to implement locomotion for VR is teleportation. With teleportation, users point to a specific destination inside the virtual environment and activate the teleportation using a button press. An example of teleportation is shown in Figure 2.14. Usually, the user gets visual feedback in the form of a line or arch for the pointing. The teleportation range is limited to a specific length or only allowed on specific (predefined) teleportation areas or spots that users can teleport to.

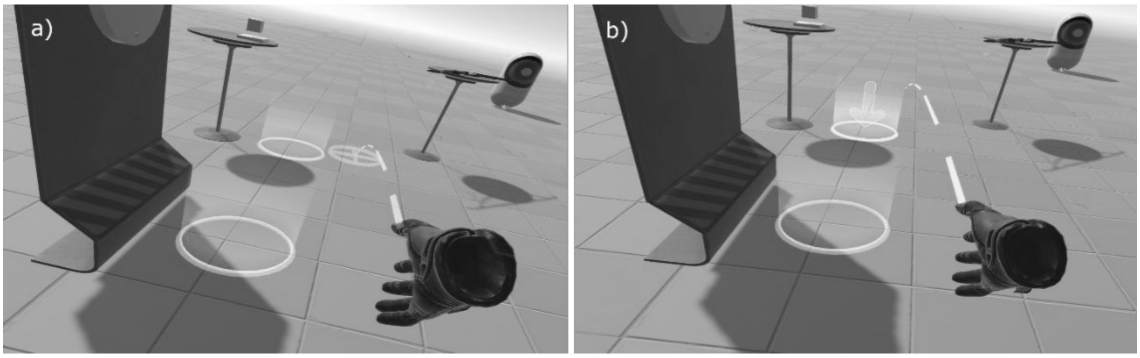

Figure 2.14: Teleportation in VR on predefined spots.

Note: (a) shows two spots the user can teleport to. The system displays a red line when the user points to an area that cannot be used for teleportation. In (b), the user points toward the teleportation point and receives positive feedback in the form of a green line. Whereas this example shows teleportation points, users might be allowed to teleport on the whole area in the VE depending on the implementation.

Whereas teleporting might be a simple way to implement and use locomotion, it is not a natural but rather an artificial way of moving forward (e.g., Funk et al., 2019). Research has shown that natural movement in virtual environments positively impacts users' feeling of presence (Steinicke et al., 2009; Usoh et al., 1999). To increase the natural ways of movement in VR experiences, research and the industry have developed and evaluated the use of treadmills and similar devices for VR (e.g., Sloot et al., 2014). Due to various factors, such as additional costs and integrating an additional device, treadmills are not always applicable. Instead, other ways of locomotion have been developed and tested. For example, Auda et al. (2019) have applied a combination of vision shifting and *Electrical Muscle Stimulation* (EMS), resulting in an 'infinite walking' VR experience where participants walk in circles. Other examples of different locomotion techniques can be found, for example, with walking in place (Templeman et al., 1999), vision shift (Azmandian et al., 2014), impossible spaces (Suma et al., 2012), or hamster ball (Medina et al., 2008), among many others.

Figure 2.15 shows a typology of different locomotion techniques proposed by Boletsis (2017). The typology identifies four different locomotion types: motion-based (e.g., walking-in-place, redirected walking), roomscale-based (real walking), controller-based (joystick, head-directed), or teleportation-based (point & teleport). The typology classifies locomotion techniques in the interaction type (either physical or artificial), motion type (continuous or non-continuous), and VR interaction space (open or limited). For example, controller-based locomotion is an artificial locomotion technique that allows continuous motion inside an open interaction space. Real walking, on the other hand, would be classified as physical interaction, allowing a continuous motion inside a limited interaction space, e.g., inside a laboratory room.

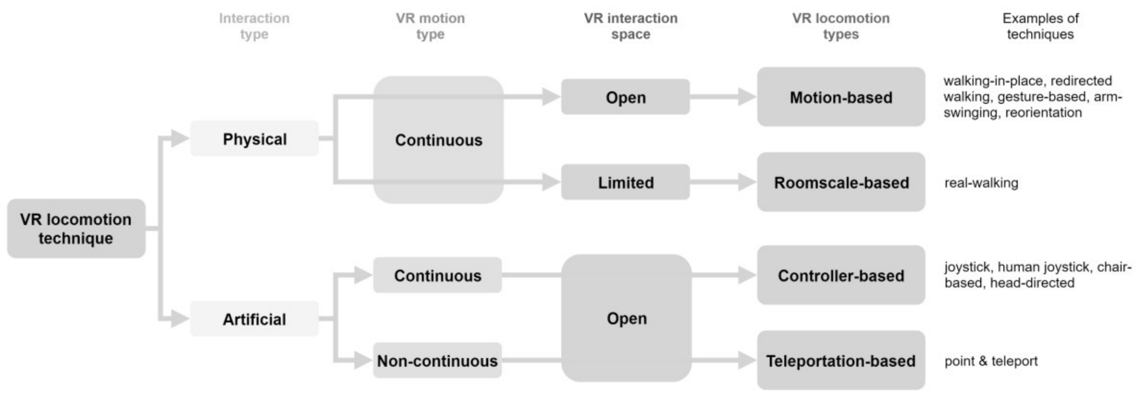

Figure 2.15: VR locomotion typology proposed by Boletsis (2019)

Note. Figure used under Creative Commons CC-BY license (CC-BY-SA)

Picking an appropriate locomotion technique for the VR experience is an important design decision that also depends on the objective of the VR experience. Whereas non-continuous locomotion techniques like teleportation might be suitable for specific research questions, other continuous locomotion techniques might be suitable for others. For example, a natural locomotion technique (e.g., roomscale-based) would support the feeling of presence. In contrast, a fast and easy way of exploring the VE by point and jump would be provided with teleportation. Thus, for the objectives of this thesis, only continuous VR motion types, are suitable.

2.3.2 Virtual Simulations in Research

Virtual simulations have been used in research for a long period of time, as simulations allow to resemble reality to a certain degree, and specified parameters can be examined in simulations before evaluating them in real scenarios. For example, research in the automotive domain has been applying driving simulators to investigate human factors (e.g., Ahtamad et al., 2015; Blaauw, 1982; Ho et al., 2006, 2007; Lincke et al., 1973; Meng et al., 2015). In early work on driving simulators, Lincke et al. (1973) discussed their advantages and challenges. Briefly summarized, the authors list the following advantages of driving simulators as they allow:

1) An accurate reproducibility of test parameters and vehicle dynamics.
2) Permit vehicle characteristics to be arbitrarily varied within a short period of time.
3) Permit recording of many input variables, including those that are difficult to measure.
4) Preclude hazards to the test subject and the equipment.

Lincke et al. also refer to two significant challenges, (1) that driving simulators only approximate realistic reproduction of vehicle behavior, therefore have limitations of the real-world validity, and (2) driver's motivation should be considered in the driving simulation, that is, reaching a destination by car in a fast and safe way (cf. Lincke et al., 1973, p. 1586).

For a comparison of driving simulators with real driving, Reed and Green (1999) compared driving performance in a simulator with driving an actual test vehicle. The performance was also compared while participants did a telephone dialing task. The authors used two scenes for the visual fidelity inside the simulator: a "high-fidelity mode" with 8-bit color and a monochrome "low-fidelity" visualization of a road. The results showed that while speed control performance was comparable between the conditions, lane-keeping was less precise in the simulator. During the dialing task, the performance decreased in both conditions, while the decrease was greater in the simulator. The high- and low-fidelity modes showed no relevant differences in task performance. The authors concluded that the simulator demonstrated good validity in assessing decrements in driving performance associated with in-car phone use (Reed & Green, 1999). A longitudinal study on the transfer of skills learned on driving simulators by Hirsch and Bellavance (2017) between 2010 and 2014 has shown that the integration of simulator-based training led to lower infraction rates of drivers compared to the group that did the mandatory driver education. However, the crash rates were comparable for both groups.

With technological progression, driving simulators have evolved into highly sophisticated, real-world emulating tools that allow producing simulators to "resemble real driving in terms of vehicle controls and the visual environment" (Wynne et al., 2019, p. 138). As an example, in the study by Ho et al. (2006), the *Transport Research Laboratory* driving simulator had a five-speed manual gearbox and an electronic motion system that allowed the system to provide “realistic vehicle dynamics such as the vibrations that would be experienced when driving an actual vehicle on the road” (Ho et al., 2006, p. 989). For the visualization, the driving simulator used three displays at a resolution of 1280x1024 pixels to provide a 210° horizontal forward view and one rear screen for a 60° rear field of view. Additionally, the apparatus used a stereo sound system to simulate the road, the engine, and traffic sounds (Ho et al., 2006, p. 989).

Recent research has also used VR to conduct driving simulation studies to utilize the immersive characteristic of the headsets (Silvera et al., 2022; Taheri et al., 2017). To investigate the interaction between pedestrians and automated cars, Holländer et al. (2019) used a VR environment of an urban traffic scenario to research how external car displays would affect participants’ decision to cross roads, among other parameters. As VR “has the advantage of a well-controlled experiment setup while still giving the subject freedom of movement and placing it in a relatively natural environment” (Clay et al., 2019, p. 1). Such simulations can be used for all kinds of scenarios, thus its immersive features are hoped to enable behavioral training for hazardous scenarios, as “Virtual Reality research allows placing people/participants into risky-appearing situations, without having actual risks” (cf. Wogalter et al., 2021, p. 657). However, whereas vehicle simulators do not require a participant to leave his/her static position in the driving seat, depending on the scenario, it is crucial to allow participants to move around the scene in VR. Thus, adequate solutions for locomotion techniques must be used (see previous section 2.3.1.4).

As an example of VR-based behavior research, VR has been used to evaluate warning compliance on (visual) warning sign research (Almeida et al., 2015; Duarte et al., 2010). The rationale for using VR is that real-time warning compliance studies are too costly to implement due to ethical and methodological challenges. In addition, controlling the variables and context in field testing takes effort. Instead, laboratory studies are performed, which limit external validity (Almeida et al., 2015). Thus, Almeida et al. argue that VR effectively enables the advantages of field and laboratory research and balances their disadvantages, providing *ecological validity*[3] to their approach.

Ecological validity refers to the extent to which results that occur under certain conditions are typical for the population at large and can thus be generalized across situations and settings. For example, ecological validity for an effect that has been proven in a lab setting is only given if that effect is happening in everyday life (cf. Brewer, 2000, p. 12). More generally, e*xternal validity* refers to generalizing results to other contexts. On the contrary, *internal validity* refers to the study design, conduction, and the extent to which biases may compromise data and results. VR offers researchers a controlled environment that allows behavior tracking, data logging, and in-depth information gathering about subjects’ actions, while the controlled conditions can be identical over multiple trials and subjects (Clay et al., 2019). With intuitive interaction methods in VR, “the

[3] According to Khorsan and Crawford (2014), *ecological validity* is also referred to as *model validity*. The authors argue that model validity is part of the external validity.

correspondence between subject movements and changes in the environment increase ecologic validity of the experimental paradigms" (Clay et al., 2019, p. 2).

VR evaluation studies follow similar principles and guidelines as system evaluations or usability tests (cf. Duarte et al., 2010; Duarte & Rebelo, 2007). Qualitative, quantitative, or mixed approaches can be applied depending on the specified research question and the actual focus of the research. Thus, applied methods may range from heuristic evaluations, investigating research questions, tasks, using questionnaires or other measures, or inviting participants. Setting up a study plan should serve as a communication document for other people involved in the study. A pilot study (or *pre-study*) may help to find and solve all bugs from the setup before the actual study is conducted (cf. Livatino & Koffel, 2007).

2.3.3 Virtual Reality in Construction Research

Due to the immersive features of VR and the absence of any real hazards, VR is used for training and research in the construction site domain, for instance, for safety training or hazard identification tasks. One of the significant benefits of VR in construction site training is that the VR environments can replicate and simulate dangerous and high-risk situations while being (physically) in a safe and risk-free environment (cf. Albert & Routh, 2021, p. 4). With the use of *Building Information Modeling* (BIM), daily updated 3D representations of real construction sites and construction buildings can be facilitated for VR training, e.g., to analyze the existence of potential hazards (Du et al., 2018; Zaker & Coloma, 2018).

Many studies for civil engineering focus on safety training in VR. For instance, a study by Sacks et al. (2013) with 66 participants investigated the effectiveness of VR-based construction safety training compared to conventional training methods. One-half of the participants received traditional classroom training, and the other half received a 3D immersive training simultaneously via a CAVE-VR setting. Each participant completed a safety knowledge test before and after the training stage. Compared to traditional training methods, VR training was more effective for risk identification, prevention, and risk level assessment in reinforced concrete works and also more effective in risk identification in stone cladding works. The researchers found VR training to be the more effective learning experience (Sacks et al., 2013). Perlman et al. (2014) have used a CAVE-VR setting to compare the identification of hazards between VR visualizations and photographs. The results of their study have shown that participants identified more hazards in the VE than in the photographs. In another example, in a study concerning multiplayer construction site safety training in urban cities, participants better memorized hazardous situations and critical points in the VR training than in traditional training methods (Xu & Zheng, 2020).

N. Kim et al. (2021) studied risk habituation in construction settings with a VR experiment. In the VR experience, participants stepped into the role of a cleaning crew in a road maintenance workplace. Their task was to sweep away debris behind a milling machine that removed the asphalt surface. Besides keeping enough distance to the milling machine, dump trucks and commuter traffic were modeled to which also enough distance should be kept. The results of this study indicate that all subjects became habituated to repeated hazards in the virtual construction simulation as they began to ignore the proximity to the hazards (N. Kim et al., 2021). The technical capabilities of VR systems allow understanding site hazard identification by using eye tracking in virtual construction environments (Ye & König, 2019).

Besides construction site safety, VR is also used for safety training in other domains. For example, in the context of machinery safety, Dado et al. (2018) have shown that VR could be a valid alternative to traditional training approaches for hazard identification training. In the context of teaching pedestrian safety, there is evidence that VR is suitable for teaching pedestrian safety to children and adults (e.g., Bhagavathula et al., 2018; McComas et al., 2002).

In summary, this section has shown that research with VR can be used as a valuable research method for the construction industry. One recurring rationale for using VR is the possibility of evaluating situations in a hazard-free environment, for instance, to research risk habituation or hazard identification.

2.3.4 Virtual Reality Laboratories

After outlining the exemplary research objectives of using VR in construction research, this section will present a more general review of the concept of *Virtual Reality Laboratories* (VR Labs). The idea of VR Labs emerged in the 1990s to enable pupils and students to learn through experience in simulations (e.g., Fellner & Hopp, 1999; Loftin et al., 1993; Slater et al., 1996). As mentioned in the sections above, the mixture of experiencing virtual simulations in a vivid and highly immersive way (section 2.3.1.2), having a high experimental control and ecological validity to a certain extent (section 2.3.2), led to VR use for many applications as well as educational and research purposes.

For instance, with a VR Lab for teaching chemistry, Georgiou et al. (2007) point out the cost-effectiveness of such VR solutions. Experiencing and executing chemical experiments play an important role in the chemistry education for comprehending theory and acquiring relevant chemistry skills. According to the authors, such costs could be reduced by implementing and using VR Labs, as the ongoing costs would decrease. Rahman (2022) also refers to the cost-effectiveness, as VR Labs would eliminate the need to think about budget and lab space.

With the implementation of own VEs, VR Labs enable researchers to conduct all kinds of behavioral studies. For instance, to conduct retail research in virtual supermarkets (Peschel et al., 2022), VR studies to research (visual) warning compliance of humans (Duarte et al., 2010), or fire evacuation research (Kinateder et al., 2014).

Kinateder et al. (2014) compared VR Lab experiments for fire evacuation research to other research methods. According to the authors, VR experiments allow a higher experimental control than classical lab or field studies, although all three have a "medium" ecological validity. They argue that VR may have a higher ecological validity than lab studies for certain research questions but not for all. Their argumentation is based on the needed features for the research question. For instance, VR Lab studies might be more suitable than ‘classical’ lab studies when a visualization of flames and fire is needed, but not, for instance, for features of touch or smell, as they might be not technically be feasible with VR. When comparing VR experiments to field studies, according to the authors, VR allows a better adjustment of experimental settings, allows to do exact replications of studies, and are more time- and cost-efficient for data collection (Kinateder et al., 2014, p. 314).

In this thesis, the idea of VR Labs will be revisited for evaluations of on-body vibrotactile warning systems. Advantages of the VR Lab approach, besides the cost-effectiveness (compared to field studies), are, that the application scenarios are customizable and configurable for the domain of interest. Thus, allowing to freely implement any scenario for behavioral studies.

2.3.5 Summary

This section has introduced VR, its hardware components, and essential concepts of the technology: immersion, presence, health and safety aspects, interaction, and locomotion. Using the mixed reality continuum, VR was differentiated from related technologies, such as AR. Then, research areas and concepts relevant to the thesis were presented. The most important were:

- Place illusion and plausibility illusion to create the feeling of a certain realism inside the VR simulations.
- Consider health issues, such as motion sickness symptoms that participants may experience, collide with surrounding objects or lose balance due to the lack of visual information from the real environment.
- Considerations for an adequate locomotion method for the VR simulations. The locomotion method should be continuous. Non-continuous locomotion, like teleportation, could lead to skipping the triggers for hazard warnings.
- Driving simulators were used to show that graphic fidelity showed no difference in driving performance. It remains to be tested whether similar effects occur with VR.
- As indicated in Section 2.2.5.3, the use case to be investigated was the evaluation of a vibrotactile PWS. Field testing of PWS in real environments is complex to be carried out. Thus, VR could be a resource-friendly alternative for such evaluations.
- The concept of VR Labs was introduced, which can be seen as an alternative research method to existing ones. In this thesis, the idea of VR Labs is pursued in order to create a test setting for evaluating vibrotactile warning wearables.

3 Design Space and Requirements

This chapter[4] introduces this thesis's overall domain and problem space, namely construction site safety. The chapter is based on a mixture of practical experiences from the third-party funded research *DigiRAB*[5] and research literature. Here, challenges of construction site safety are described, accident rates are discussed, and typical hazards and challenges of hazard avoidance are presented. The chapter also discusses the use case of Proximity Warning Systems (PWS), a sensor-based warning approach for construction work, and challenges in evaluating such warning systems in real-world environments.

To develop a VR Lab for research in a specific domain, first, the contextual factors of the domain need to be understood. Therefore, this chapter outlines the design considerations of a VR research laboratory:

1) The thesis is motivated by accident numbers and typical types of accidents on construction sites. Observations from safety inspections of construction sites are presented and translated into design requirements. Finally, the use case of proximity warnings is presented and a transfer into VR is proposed.
2) Requirements for the vibrotactile signals are extracted from the related work and mapped to the use case. In this context, it will also be examined which body placement of tactile signals would be conceivable and how these can be implemented.
3) The design space of VR is analyzed and related to the use case of proximity warnings. This analysis also determines which aspects are essential for designing immersive 3D worlds of the corresponding application areas

[4] Parts of this chapter have been published in:

Jelonek, M., & Herrmann, T. (2019). Attentiveness for potential accidents at the construction site: virtual reality test environment with tactile warnings for behavior tests in hazardous situations. In *Proceedings of Mensch und Computer 2019* (pp. 649-653).

Jelonek, M., & Herrmann, T (2020). Process-Oriented Collaboration to Identify Socio-Technical Measures for Construction Site Safety. *Poster Presentation at 26th International Conference on Collaboration Technologies and Social Computing (CollabTech 2020)*.

[5] DigiRAB = „**Digi**tale **R**egeln zum **A**rbeitsschutz auf **B**austellen“ (Digital rules for occupational safety on construction sites).

The project was funded by the German Federal Ministry of Education and Research (BMBF) and the European Social Fund (ESF) within the Framework Concept “Innovations for Tomorrow’s Production, Services, and Work” (02L15A170) and managed by the Project Management Agency Forschungszentrum Karlsruhe (PTKA-PFT).

investigated. Then, the VR-specific characteristics are discussed and referenced to real-world movement, perception, and others.

The approach used is similar to the proposed method of Duarte and Rebelo (2007), who evaluated the effectiveness of visual warning signs with VR studies. The authors proposed the following four main steps in VR research: (1) Define the scope of research and the context that is relevant for that research, (2) use an iterative modeling process using low-fidelity prototypes up to the modeling of the 3D virtual environment, (3) collect data by conducting the study with participants, and (4) analyze the data for results and conclusion (p. 194).

3.1 Understanding the Field: A Socio-Technical Analysis

In urban areas, construction sites can be found almost everywhere, from minor to larger construction sites, in the field of rail works, roads, tunnels, or sidewalks, with more or less severe restrictions for the surrounding infrastructure. While smaller construction works are relatively comprehensible for outsiders, the construction process of larger construction sites can be considered a complex socio-technical phenomenon (Jelonek & Herrmann, 2020), as many different (sub-)companies and trades are involved in such construction, and thus correspondingly different equipment and personnel (as discussed in section 3.1.5). In the project *DigiRAB*, construction projects were regarded as *Socio-Technical Systems* (STS). The concept of STS arose in the 1950s out of two research projects by the Tavistock Institute in the British coal mining industry (cf. Trist, 1981, p. 7). STS emphasize that organizations should not be solely regarded as technical systems but as to give “equal weight to social and technical issues” (Mumford, 2000, p. 125). Thus, STS design focuses on social, organizational, and technical factors and processes (Baxter & Sommerville, 2011, p. 4). Obtaining an extensive understanding of the domain and the processes within is essential for VR research, in this case especially focusing on safety aspects.

To give a vivid example for the complexity to understand construction process, an observed incident of construction site hazards occurred during the finalization of writing the first draft of this thesis in 2022. While the neighboring university building was being renovated down to the ground, the demolition work could partly be seen from a distance (Figure 3.1). One day, during debris removal, several construction workers dragged a container that was held by a crane closer to the building. Dragging the container allowed construction workers on the floor above to throw the debris into the container more easily, risking the workers below being hit by debris at any time.

Figure 3.1: Throwing debris into a container, above of other workers (Picture by Felix Thewes, 2022)

However, at this point, the observed work cannot be evaluated in more detail from the outside. While the apparent threat for the workers is evident (overlapping of construction workers, as the workers on the lower level were always exposed to the danger of objects falling from above), it remains unclear from the outside why this sequence has occurred. Maybe technical circumstances prevented placing the container closer to the building, or maybe other factors were involved. However, this example shows that more than an outside analysis is needed to understand the exact processes in construction processes.

The following subsections provide insight into typical hazards, work, and potential safety solutions for construction work. Besides providing a better understanding of the field, the following sections also are used to gather requirements for VR simulations.

3.1.1 Analysis of Construction Site Accidents

The construction industry has a history of high accident rates and fatalities (e.g., Abdelhamid & Everett, 2000; Haslam et al., 2005; Namian et al., 2020). In many countries, more fatal accidents occur in the construction industry than in any other industry (Suraji et al., 2001). For the German construction industry, construction site accidents are reported to the *Berufsgenossenschaft der Bauwirtschaft*[6] (BG Bau). Accident numbers of all industries are reported to the *Deutsche Gesetzliche Unfallversicherung*[7] (DGUV). Over the years, the accident numbers for the German construction industry have been quite consistent (see Figure 3.2 for the number of fatal accidents between 2016-2021). In 2020, the construction industry had, compared to other industries, also the highest number of accidents and fatal accidents, averaged by the number of employees (DGUV, 2021).

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[6] Institution for statutory accident insurance and prevention in the construction industry

[7] German Social Accident Insurance

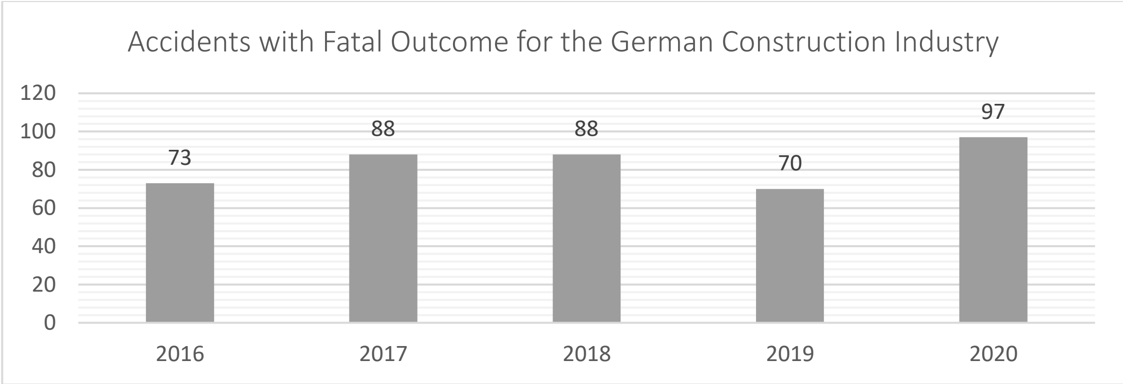

Figure 3.2: Overview of Fatal Accidents for the German Construction Industry 2016-2020

Several various root causes and reasons are considered to have an impact on the high number of accidents. These root causes include the lack of knowledge or training of workers to carry out tasks in a safe manner, missing or non-use of personal protection equipment (PPE), or inattention to hazards, among others (e.g., Perlman et al., 2014; Sawacha et al., 1999). Additionally, construction sites are considered highly dynamic environments where the environment changes on a short-term basis.

Suraji et al. (2001) analyzed 500 accident records in the *U.K. Health and Safety Executive* to develop a causal model of construction accident causation. In their analysis, the researchers distinguish between proximal factors directly impacting accidents and distal factors that lead to introducing proximal factors in the construction process. Such proximal factors include inappropriate construction operation (in 88% of the analyzed construction accidents), e.g., inadequate working platforms, including no guardrails, inappropriate operative action (29.8% of the analyzed accidents), or improper or inadequate use of PPE. Distal factors, for instance, include cost or time constraints (pp. 337–339).

Namian, Albert and Feng (2020) have shown that distractions affect hazard recognition performance and concluded that distractions might impede the ability of workers to quantify the safety risk rationally. The authors compared two groups during a hazard recognition task, one with and the other without distractions. The results have shown that the distracted group recognized fewer hazards than those without distractions. In contrast, no difference in the level of perceived safety risk was found between both groups. The study's results argue for an automated hazard alerting system, as workers could be notified during distracting tasks to shift their attention toward an incoming hazard alarm.

The causes of accidents can be manifold. In the annual statistics of the DGUV, however, more abstract categorizations are named, which are listed as examples for the year 2020 (see Table 3).

Table 3: Reported Accidents for the German Construction Industry 2020

Cause for injury	Reported Accidents		Fatal Accidents	
	Count	%	Count	%
Contact with electric current, temperatures, hazardous substances	3.307	2.8	5	5.6
Drowning, covered, wrapped up, buried under	170	0.1	7	7.9
Impact on/against a stationary object (the injured person was moving)	28.083	23.9	52	58.4
Being hit/colliding with a moving object	16.782	14.3	10	11.2
Contact with a sharp, pointed, hard, rough object	42.105	35.9	1	1.1
To be jammed (in), squeezed (in), crushed, etc.	8.505	7.2	13	14.6
Acute physical or mental overload	17.841	15.2	0	0.0
Other	534	0.5	1	1.1
Total	117.327	100.0	89	100.0

Note. Data taken from the annual statistics of the DGUV (2020).

The most percentage of listed accidents are labeled as "contact with sharp, pointed, hard, rough object", which according to the DGUV includes all kinds of tools or power tools such as (chain-)saws, knives, or other materials. Even though this type of accident is the most common type of accident reported at 35.9%, accidents of this type are rarely fatal (one reported case for 2020). Accidents labeled "impact on/against stationary object" are related to slip, trip, and fall (STF) accidents and any other accident where the injured person is moving into a stationary object. This type of accident involves over half of all fatal accidents (58.4%). Other accident types include "to be jammed, squeezed, or crushed" (7.2% of reported accidents), the contact with substances (2.8%), or others.

Although not directly stated by the DGUV, the category *impact on/against stationary objects* includes fall accidents, which often have severe or fatal consequences. In a report by the *Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA)*[8] published in 2017, falling accidents are held responsible for more than one-fourth of all recorded fatal occupational accidents over all industries in Germany between 2009-2016. According to this report, 1499 fatal occupational accidents occurred during the period. 423 of these accidents (approx. 28.2%) were caused by falls from heights. Of the 423 accidents, 269 occurred on construction sites (approx. 64.7 %). In 49 cases, falls from heights of less than 2m resulted in fatal accidents (BAuA, 2017). On German construction sites, fall protections must be installed at heights of 2m for fall accident prevention. Under certain circumstances, such fall protections are already necessary at heights of 1m, e.g., for

[8] English translation: Federal Institute of Occupational Safety and Health

stairways, wall openings, or work close to water. An example of fall protection is shown in Figure 3.3.

Figure 3.3: Fall Protection (red planks) to prevent falls from heights

3.1.2 Construction Site Safety Measures

Construction work includes all kinds of full-body activities, as well as the use of technical equipment and machinery. This section overviews contextual factors inside the construction work processes. It serves to generate a fundamental understanding of challenges and opportunities for technical solutions inside the construction domain. When designing technical solutions, a crucial part at the beginning of the design process and design methods in HCI and other areas is to understand the (potential) users, the context, and the tasks that are carried out (cf. J. D. Lee et al., 2017, p. 25). Among other things, construction site workers operate in a dynamic environment where it can be noisy, and many hazards are present. Additionally, construction sites are not easily accessible for field research. Therefore, the construction domain is highly interesting to evaluate the use of VR simulations. Even smaller construction sites can quickly become visually demanding due to clutter, deposited material, debris, or other things (see examples in Figure 3.4 and Figure 3.5).

Figure 3.4: Traffic route for construction vehicles past office and recreation containers (Photographed in Essen, Germany, 2021)

Therefore, construction work is a cognitively demanding task, as workers have to fulfill their tasks, navigate through cluttered spaces, and care for their safety and the safety of others. Additionally, construction sites are very dynamic and rapidly changing work environments (example in Figure 3.5). As construction progresses, parts of the site change rapidly, and construction workers must always expect to find changes in their work environment and the emergence of hazards. These changes also refer to the number and types of different trades, construction vehicles, and machinery, which may change between the construction stages. In addition, the surrounding environment of the construction site can impact safety, for example, if water bodies are adjacent or if busy roads or sidewalks border construction sites. In addition, noise is a constant nuisance on construction sites that can cause permanent physical damage (noise-induced hearing loss), as noise levels near heavy machinery or power tools can be around 100 dB (Ringen et al., 1995, p. 178). These noise levels may impact workers' safety, as auditory warnings, like reverse beepers on trucks or shouted warnings by other workers, might get overheard.

Figure 3.5: Example for complex and rapidly changing environments (Slussen, Sweden, 2019)

To prevent accidents on construction, the construction industry uses different approaches sites to increase safety measures, like the use of warning signs, Personal Protection Equipment (PPE), accident prevention safety trainings, and others. The measures vary in scope depending on the level at which they are implemented, as organizational safety measures have a different scope than PPE. A principle defining how to cope with safety issues is the Hierarchy of Controls (or Hierarchy of Hazard Controls), shown in Figure 3.6. According to the hierarchy of controls, the most effective way to cope with an existing hazard is trying to remove the hazard physically. In contrast, using PPE is rated as the least effective safety control measure (e.g., Albert & Routh, 2021, p. 6).

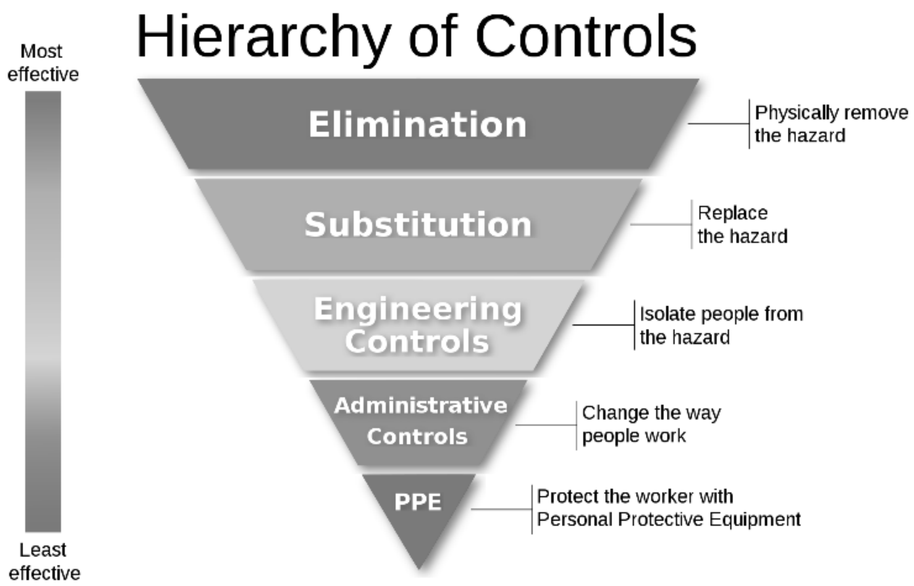

Figure 3.6: Hierarchy of Controls to cope with existing hazards. Source: NIOSH (2022)

In addition to dealing with safety measures, efforts are also made to avoid safety-critical points as early as the planning stage of construction sites. However, such places cannot always be avoided due to local conditions, which is why, for example, traffic routes for personnel and vehicles have to be clearly marked by traffic and warning signs. An example unclear routes is shown in Figure 3.7, as pedestrians are not allowed to use the right path, but this is not clearly indicated by signs. Warning signs can indicate potential hazards, but due to their static nature, they cannot indicate situational hazards that may arise during construction work.

According to Laughery and Wogalter (2006), warning systems are effective when warnings capture attention, thus will be noticed and encoded/interpreted. To encourage the encoding of warnings, they should be "sufficiently conspicuous" by providing all the "information needed for recipients to make informed decisions regarding compliance" (Laughery & Wogalter, 2006, p. 242). Although this guideline was developed for warning signs, based on Wogalter's C-HIP model (e.g., Wogalter, 2006), it can be transferred to a personalized warning system, as only noticeable and interpretable warnings allow workers to decide further actions.

Figure 3.7: Example of unclear traffic routes

3.1.3 Construction Site Safety Inspections

Methods of contextual inquiry allow the understanding of contextual environments and uncover hidden insights about domains of interest. Between 2017-2020, during the research project DigiRAB, the author attended and inspected five large construction sites with construction site safety officers in Frankfurt (Main) and Cologne. During these safety inspections, observations were noted and discussed afterward with safety officers and other representatives. Although the data is not serving as a full ethnographic basis for the requirement acquisition, the safety inspections and the discussions with experts have supported to gain an understanding of the domain and made the safety challenges vivid, as many safety hazards could be witnessed live during these inspections, listed in Table 4. Most importantly, the safety-critical events and hazards experienced on construction sites should serve to model a realistic VE of the domain. Although not all of these observations are of (direct) relevance for this thesis or can be analyzed in their fullness, they are helpful for modeling a realistic site environment.

In the project *DigiRAB,* it was also possible to review real accident reports from a construction company with one of its safety inspectors. While the reports contained some information about the accident, none of the accident reports that were viewed made it clear how the accident occurred, and which process led to the accident. Therefore, no real accident trajectories can be used for the requirements analysis. However, they are based on so-called near-accidents, in which applicable safety standards were violated and, potential accidents could have happened (Table 4).

Table 4: Observed Hazards during Safety Inspections and their Implied Risks

#	**Observed Hazard**	**Risk(s)**
H1	Trades that worked on top of each other on two floors	- Falling objects from heights
H2	Work areas not clearly delineated	- Risk of entering the area - Being hit by flying objects
H3	Missing or defective fall protection (e.g., safety fence)	- Falling from height
H4	Too much space between the construction shell and the scaffolding	- Falling from height
H5	Use of loose boards instead of suitable stepladders to reach elevated levels	- Slip, Trip and Fall
H6	Walking paths not clear of construction debris or material	- Slip, Trip and Fall
H7	Use of unsafe ladders	- Falling from height
H8	Chainsaw placed at the edge of a plateau	- Falling object from height
H9	Use of defect hook safety lock on the crane hook	- Falling objects from height
H10	Working at heights without adequate PPE	- Falling from height
H11	Crossing paths of workers and vehicles	- Being hit by moving objects
H12	Noise and dust wiping due to vehicles	- Eye injuries - Hearing loss - Overhear warnings
H13	Construction workers not wearing their PPE (observed cases: missing helmet, vest, eye shield, and ear plugs)	- Injuries due to falling objects - Being overlooked and hit by moving vehicle - Eye injuries - Hearing loss
H14	Holes in the ground without safety measures	- Falling from height - Falling objects from height
H15	Handling and guiding the crane load on the ground	- Being hit by moving objects
H16	A worker standing in the pivoting range of the excavator	- Being hit by moving object
H17	On an underground floor, a worker was not using enough lighting (~15lx), and the environment was too dark	- Slip, Trip and Fall - Oversee hazards
H18	On an underground floor, hammering noises and power tools resound while a worker was not using earplugs	- Hearing loss - Overhear warnings

3.1.4 Design of Proximity Warning Systems for Virtual Environments

As briefly discussed in section 2.2.5.3, a prominent research use case for construction site safety is the use of *Proximity Warning Systems* (PWS). A PWS is meant to function as a combination of PPE and a technical environment that allows systems to notify each other based on proximity. In summary, a worn sensor notices the signal sent by an antenna on a vehicle that is approaching and sends a warning to the pedestrian worker and to the driver as soon as the worker is inside a specified warning field of the vehicle (orange area in Figure 3.8). Depending on the implementation, such systems can be used only to send warnings to workers or even automatically stop approaching vehicles in case of danger (Schiffbauer & Mowrey, 2001).

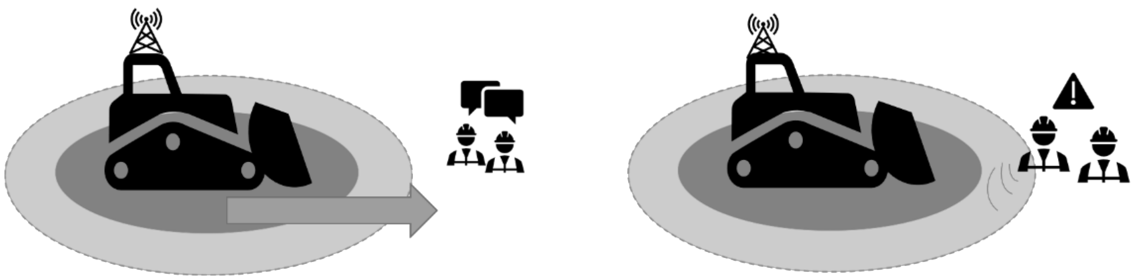

Figure 3.8: Concept of a two-level proximity warning system in case of approaching vehicles

Researchers have investigated various sensing technologies to track objects on construction sites or to detect the distance between vehicles and objects. For instance, Schiffbauer and Mowrey (2001) used low-frequency and low-power magnetic fields produced by an antenna attached to vehicles and allows the detection of receivers attached to workers. Carbonari et al. (2011) have presented a prototype that uses an ultra-wideband position tracking system to detect danger zones to prevent workers from entering predefined areas or to prevent them from being under moving suspended loads. Such systems can be understood as proactive or early-warning systems in which the system triggers a warning message towards workers because of a specific hazard before this hazard becomes immediate, therefore giving the recipient of the warning message enough time to understand the implications of the warning message and supporting the recipients' decision process. Another example of such a proactive warning system that has been researched is the mining industry's mobile Person Detection System (PDS) (Teizer et al., 2021). The system is based on Radio Frequency Detection (RFID). With an appropriate antenna, construction machines can be equipped with the PDS and then have a detection field of about 30m in diameter in length and about 22m in width for width.

A review by Ruff (2003) lists four types of object detection approaches for PWS: pulse radar systems, electronic tag-based systems (e.g., RFID), GPS-based systems (Holden & Ruff, 2001), and computer-assisted stereo vision attached to vehicles. Other examples are object recognition and worker detection via cameras attached to construction cranes (Sutjaritvorakul et al., 2020), the use of Bluetooth-Beacons and Bluetooth Low Energy (BLE) (Baek & Choi, 2018), RFID and ultra-wideband sensing (Jo et al., 2019), or virtual fencing logics (Carbonari et al., 2011). Depending on the system used, detection distances may vary. For instance, with RFID, the detection distance did range between 3-8m (Jo et al., 2017, p. 14) or around 30m (Teizer et al., 2021), whereas GPS allows tracking in much larger distances. However, whereas the transmission of warning messages concerning particular warning areas via an adequate system is a technical challenge, this thesis analyzes the human-technology component, i.e., according to whether and how humans notice the transmitted message by utilizing the tactile sense.

In order to review which evaluation methods have been used for PWS so far, a literature search was conducted using the Scopus[9] database with the keyword "Proximity Warning System" within the titles, abstracts, and keywords of research articles. The objective of

[9] www.scopus.com

this literature review is to find out how human factors of such PWS were evaluated. The search resulted in 139 research articles (137 articles after removing two duplicates). Then, in the first scan, articles were removed that related to ground proximity warning systems for airplanes and aircraft (e.g., Breen, 1999; Loomis et al., 1999). Such systems inform pilots of flying near the ground or of obstacles. Thus, in this step, 102 articles were removed. In a second scan, the 32 remaining articles were scanned for their evaluation approach of PWS. Articles were removed when they were inaccessible, did not report an evaluation with humans but only a technical 'proof-of-concept', or when the evaluation did not include a warning device. The remaining nine papers were analyzed for their PWS approach, the applied warning method, and the evaluation Table 5. The evaluation approaches are categorized to:

- 'Technical' evaluations, meaning human participants were involved in the evaluation, but the test focused on technical effectivity in general (e.g., detection accuracy),
- 'Artificial', when the evaluation was done with human participants, but their task was not based on a real task (e.g., standing still and responding to a warning), and
- 'Realistic', when the participants were doing realistic and practical tasks or tasks that were based on real ones.

This distinction is relevant since the validity of field test results with artificial tasks is likely lower than that of field tests with realistic tasks, and the overall workload may differ between the two types of tasks.

The analysis of literature reveals the difficulties to create realistic evaluation settings of such warning systems, as most articles have presented technical evaluations or artificial ones. From the data set, one paper used a field experiment with drivers (T. Ruff, 2006), and only one research papers used a field experiment to capture workers' responses to a PWS (Luo et al., 2016). However, even in that research the experiment was limited to *static* hazards (e.g., unprotected roof edges, roof, and floor openings), as mobile hazards (e.g., crane load, vehicles) would put participants in danger.

Table 5: Proximity Warning Systems in the Literature

Reference	**Warning Message**	**Evaluation Method**
Baek & Choi, 2018)	Visual on Smartphone	Technical field test: Vehicle driver approached a pedestrian worker 50 times.
(Baek & Choi, 2020)	Visual on Smart glasses	Technical / artificial field test: Vehicle approached a pedestrian 40 times from different angles.
(Chan et al., 2020)	Visual LED in helmet	Technical and artificial tests: workers (real) field-of-view was streamed into a VE and a spatial analysis was performed in the VE that resulted in personalized warnings.
(Jo et al., 2017)	Visual LED in helmet and audible via speaker	Technical lab and field tests: Lab: RFID detection area was tested under perfect conditions. Field: worker approached a vehicle, and in a second field test, a vehicle approached the worker. The RFID detection area was measured.
(Y. Kim & Choi, 2022)	Vibration (Smartphone) Visual LED in helmet	Technical field test: Vehicle approaching worker from 0°, 15°, and 30° to measure detection accuracy
(K. Kim et al., 2017)	Visual on Smart glasses	Technical field test: Effectiveness of the image tracking system Artificial laboratory tests: Participants' response times on warnings and identification of direction. In a second test participants had to solve a puzzle and had to detect entering the specified area by the experimenter.
(Y. Kim et al., 2021)	Visual LED in helmet	Technical / Artificial field test: Truck in minefield approached pedestrian workers 50 times. Warning method was compared to others.
(Luo et al., 2016)	Verbal warning via device	Realistic field test: 72 workers used a PWS for 17 days in a viaduct construction project.
(T. Ruff, 2006)	Audible (Audio Pulses)	Realistic field test: PWS was attached to a truck for seven days, driver got warned when PWS detected objects on the rear of the truck.

With game engines (for creating VEs), it is possible to implement and simulate such scenarios easily. A worker's intersection with a vehicle's warning area can be implemented with game engines via colliders[10] (example shown in Figure 3.9). Colliders enable game engines to perform physical calculations of object collisions. As soon as the two colliders overlap, a corresponding event will be processed to forward the warning to the worker (the VR user). This way, every imaginable scenario can be designed virtually, even ones that are technically (yet) not feasible in real environments. With the used approach as shown in Figure 3.9, the warning area (the collider) is static around a defined mid-point. For a more realistic virtual simulation, it would be possible to integrate the

[10] https://web.archive.org/web/20231013153152/https://docs.unity3d.com/Manual/Colliders Overview.html

results from the studies into the VE and thus generate dynamic collider sizes in real-time to simulate interference in the signals.

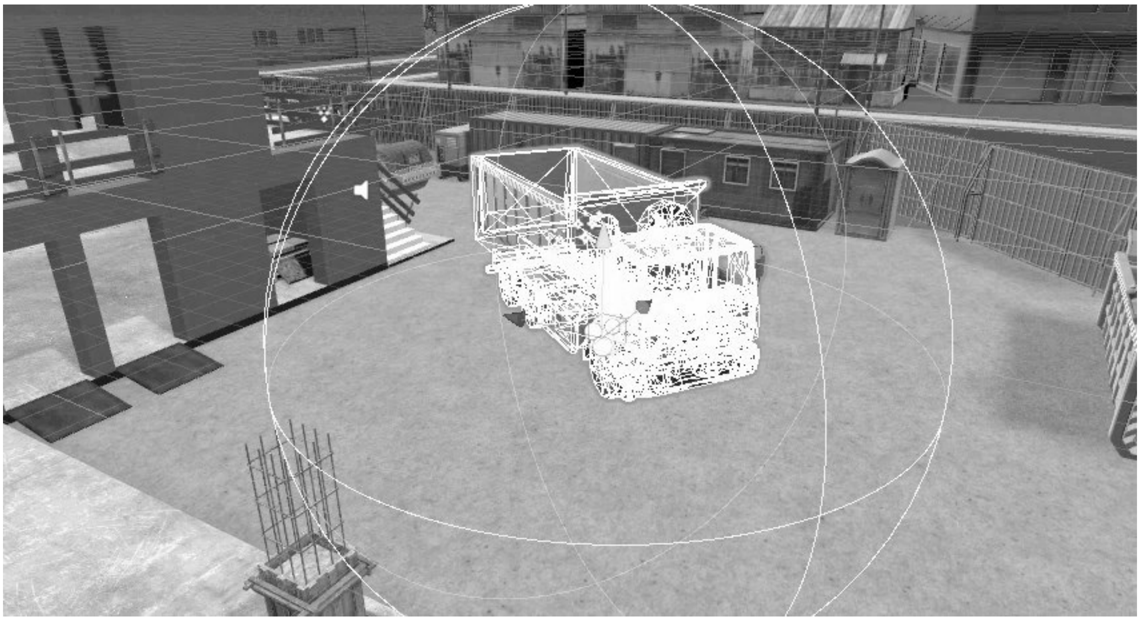

Figure 3.9: Colliders (lines) allow to recognize events in VEs, i.e., when multiple objects touch

3.1.5 Socio-Technical Perspective on VR Simulations in Construction

With the high number of occupational accidents in the construction industry (section 3.1.1), it is tried to apply BIM to improve safety throughout the whole construction process (e.g., Qi et al., 2012). BIM serves as a full digital representation of construction sites and buildings, including 3D representations, organizational and technical information. Over the course of construction projects, the model is enriched with more and more information (Figure 3.10). Regarding safety aspects, BIM has been used, for instance, to support site safety planning through the visualization of BIM-based site layout planning (Sulankivi et al., 2009).

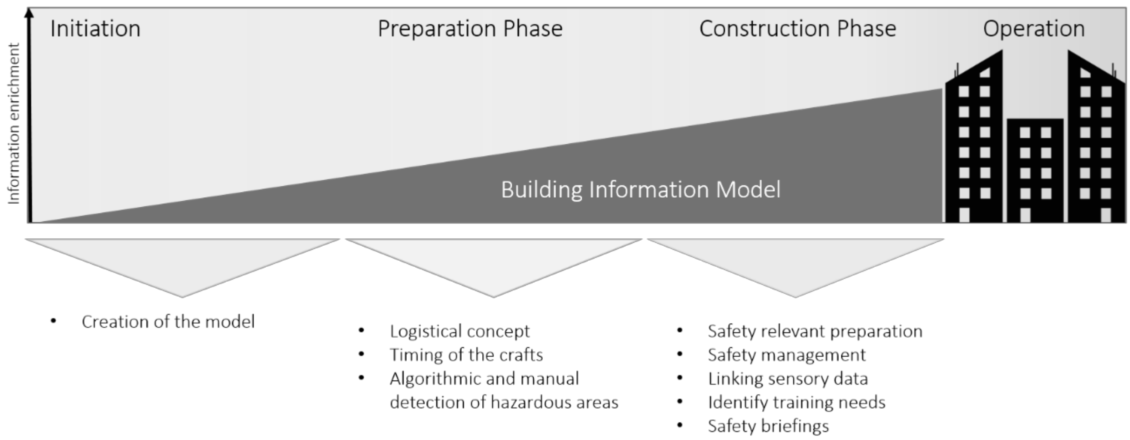

Figure 3.10: Information Enrichment of Building Information Models throughout the construction projects, with exemplary tasks displayed for each project phase.

During the research project *DigiRAB*, it was investigated how BIM could be integrated into the construction process for occupational safety, for instance, by applying rule checking algorithms to automatically highlight safety relevant spots in the models.

To capture the organizational, technical and social complexities of construction processes, the method of *Socio-Technical Walkthroughs* (STWTs) was applied (Herrmann, 2009; Herrmann et al., 2007). The method allows to structure communication of process design teams, uses rigid questioning to create intensive discussions on individual process steps, and combines analytical and associative thinking (Herrmann, 2012). The process was designed with the *SeeMe*-modeling notation[11] (Herrmann et al., 1998; Herrmann & Loser, 2001). The SeeMe notation is an easy-to-grasp semi-structured modeling notation that allows vagueness in its models (Herrmann & Loser, 1999).

Within the project *DigiRAB*, the author conducted and was part of ten iterative socio-technical walkthroughs (STWTs) to capture the current socio-technical process of a larger construction company in Germany with SeeMe. These STWTs were conducted together with BIM experts, safety inspectors and project managers. The approach followed the objective of first assessing the ACTUAL process to then design a TARGET process that highlights the integration of BIM. The process model grew iteratively from workshop to workshop, and the respective process segments were discussed several times, adjusted where necessary, and verified. However, here only the beneficial use and integration of VR simulations into the process are discussed and a very shortened and simplified extract of the target process is shown in Figure 3.11. The whole TARGET process is added to the Appendix B. Note that no roles are integrated into the process. Role concepts were partly not defined at the time of process creation. In addition, adding roles would have further complicated the process visualization and made it more difficult to overview.

[11] A very brief overview of the base elements (roles, activities, and entities) and relations of the SeeMe notation are added to the Appendix A. For a full overview, the documentation 'SeeMe in a Nutshell' (Herrmann, 2006) should be referred, as well as the references provided there.

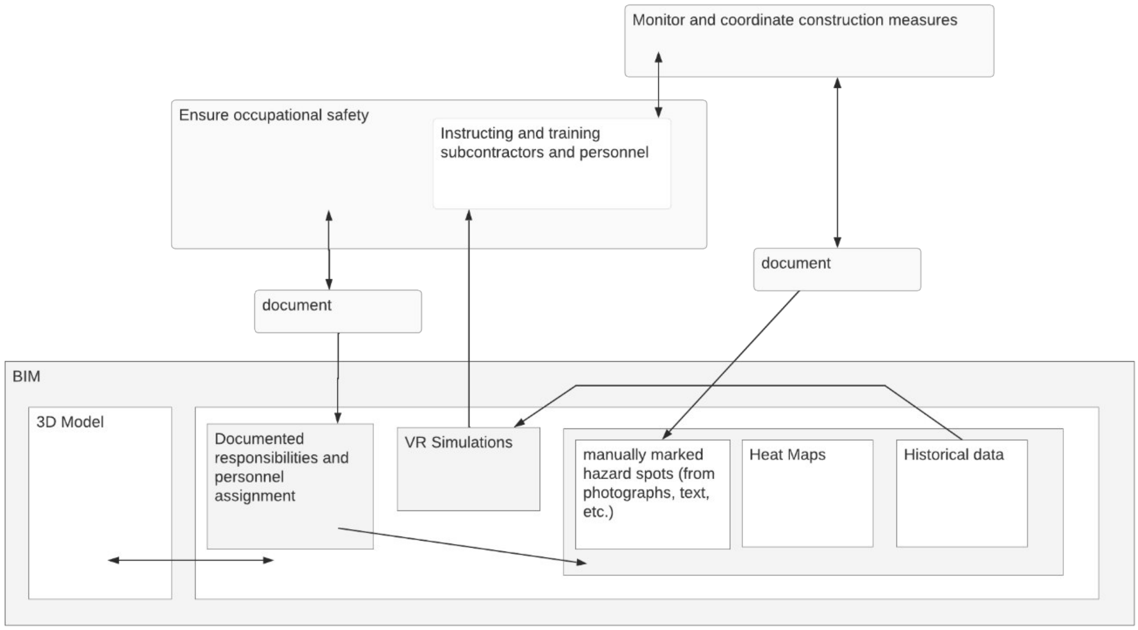

Figure 3.11: Shortened extract from the BIM-based TARGET construction process (see Appendix B for the complete process).

From the analysis it became clear, that one motivation to use VR simulations is for instruction and training purposes, e.g., by applying VR safety trainings. Such training can be based on historical data given a suitable data set. This could, for example, include accident data or near miss data from a construction site. Using BIM, an extracted 3D-model could be used for the basis of a VR simulation. Accordingly, with daily updated 3D models, a VR simulation could theoretically be based on the current status of the construction site. In theory, one could even use the models of future construction stages to analyze safety-critical spots on the site with VR training in advance, before the construction building has reached that stage in reality. Thus, VR could enable immersive safety-inspections of construction stages based on the created 3D models.

3.1.6 Summary of Contextual Requirements for VR Labs

Based on the abovementioned areas, following is a tabular summary of requirements for the virtual construction site (the VE) and its related depiction of hazards. For easier traceability in the further course of this thesis, the requirements are given an identifier, and the chapters are mapped to the requirements from which the requirement originated.

Table 6: Requirements for the virtual environment of the construction domain

ID	Requirement	Origin
REQ VE 1	In the virtual construction site, many hazard locations should be integrated	3.1.1; 3.1.2
REQ VE 2	The VE should integrate the different accident categories and hazards	3.1.1; 3.1.3
REQ VE 3	The VE should integrate proximal factors of accident causation	3.1.1
REQ VE 4	(Visual) distractions should be incorporated into the VE	3.1.1
REQ VE 5	The VE should reproduce the noisy environment of construction sites	3.1.2
REQ VE 6	The construction site should appear (visually) cluttered to resemble real construction sites	3.1.2
REQ VE 7	The VE should integrate the dynamic and rapid changes in construction sites	3.1.2
REQ VE 8	The tasks on the virtual construction sites should be based on the 'full-body' activities	3.1.2
REQ VE 9	Hazards from the surrounding environment of the construction site should be incorporated	3.1.2
REQ VE 10	Other trades and workers should be included.	3.1.1; 3.1.2
REQ VE 11	The activities in the virtual construction site should be cognitively demanding	3.1.2
REQ VE 12	In the VE several personal protective equipment should be implemented	3.1.2
REQ VE 13	Situational hazards should be integrated	3.1.2
REQ VE 14	The warnings in the VE should capture attention and can be interpreted correctly	3.1.2
REQ VE 15	Hazards that were observed should be integrated into the VE	3.1.3
REQ VE 16	The use case of proximity warning systems should be implemented and evaluated	3.1.4
REQ VE 17	Several detection ranges of PWS should be implemented to reflect the different PWS approaches	3.1.4

3.2 Design of a Vibrotactile Wearable

This section discusses parameters to consider when designing vibrotactile wearables. Based on the use case of PWS, such a warning system needs at least two entities that can communicate with each other: A *Transmitter* and a *Receiver*. In the example shown in Figure 3.8, warnings should be sent to machine operators and workers, in the best case, bi-directionally.

To receive warning messages, workers must wear a technical device. As construction workers rely heavily on their visual and auditory systems to work and navigate safely on construction sites, researchers have investigated using the tactile sense to receive warnings (e.g., Cho & Park, 2018). Such an approach is based on contextual factors, as construction noises can be deafening. Thus, auditory alarms might get overheard. Similarly, visual warnings might get overlooked due to the many movements and objects on construction sites. With the high visual and auditory demand on construction sites, following Wicken's multiple resource theory (see Section 2.1.3.3), transmitting warnings via the tactile sense could be helpful to avoid any bottlenecks in the visual or audio information processing.

3.2.1 Conceptual Design

The transmission of vibration to a person's body, for example, when receiving a notification via a smartphone, can be understood as a binary information transmission. As long as no vibration occurs, there is no information, hence, no warning. As soon as a vibration occurs, there is information. However, vibrotactile signals also allow for more complex information transfer across different parameters, such as body placement, pattern, intensity, or rhythm (see Section 2.2.4). Whereas the latter are all configured by the vibrotactile signal itself, body placement is a design decision that concerns the design of the wearable.

Based on previous research and the design guidelines for wearability provided by Gemperle et al. (1998), the upper body is chosen as body placement for the vibrotactile feedback. This body part has a large surface area compared to other body parts and generally has a low movement. Due to the physical work on construction sites, the placement of vibrations on hands is comparably less suitable since the hands are used for all craft activities, and the sensitivity of the vibration and the longevity of the wearables would be questionable. When considering the flexibility of human movement, the placement of the wearable around the upper body does not interfere with the person's ability to move around.

Furthermore, the warning system should warn of dangers from all possible directions. This aspect becomes especially relevant when a moving hazard approaches the worker unknowingly from behind. To translate the vibrotactile feedback for all directions, the torso, i.e., waist, chest, and head, are particularly suitable. Therefore, a wearable around the waist could allow to direct into all cardinal directions (Figure 3.12) and even in-between (Pielot et al., 2008). For instance, such tactile belts that display the direction on a horizontal line around the waist has been studied for navigational tasks (Pielot et al., 2009) or building-clearing tasks (Lindeman et al., 2005). In this thesis, at least four cardinal directions will be evaluated by placing vibration motors around the waist: on the front, the back and the left and right side of the waist. Finally, the different abdominal and chest circumferences have to be considered. The wearable should be suitable for different body sizes.

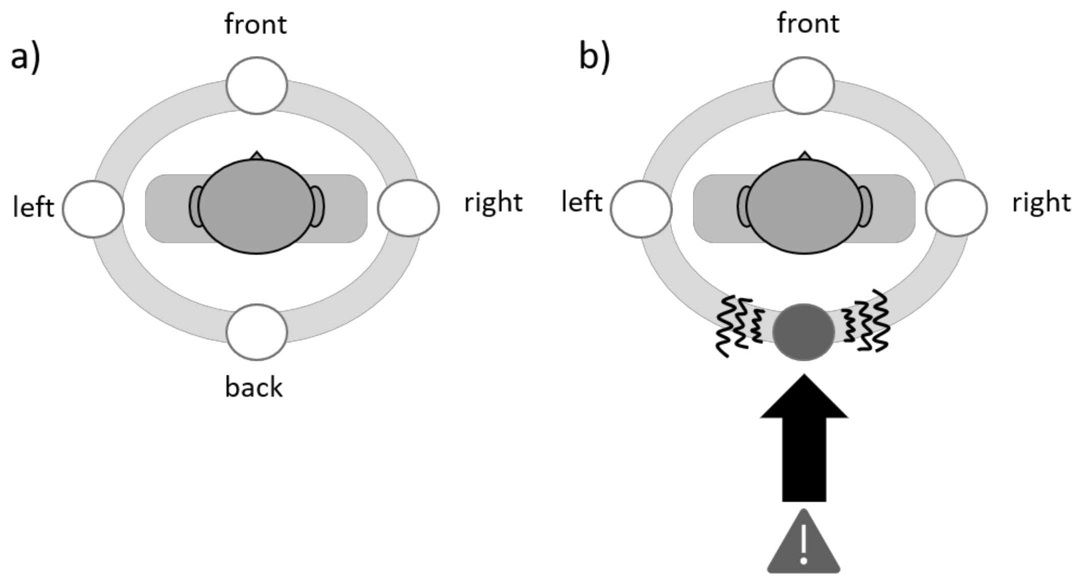

Figure 3.12: Visualization of the vibration directions (a) and a vibrotactile warning when an object approaches from behind (b).

3.2.2 Design of Vibration Warnings

Warning systems need to be designed in a way that allows recipients to always notice the warning. Design guidelines and the literature provide guide the design of vibrotactile applications. For instance, design guidelines by van Erp (2002) focus on signal detection, information coding, and comfort. In the case of a warning system, alerts should be the exception rather than the rule; therefore, the comfort aspect of vibrations can be neglected, although they should not cause pain. Moreover, in the end, there is no need to weigh safety-critical warnings against the convenience of a warning. Regarding the detection, for the lowest thresholds, vibration frequencies should be in the range of 200-250Hz. Considering the tactile information coding, the placement/location of vibration signals the critical information of hazard direction. According to the guidelines, no more than "9 different levels of frequencies should be used for coding information" (Van Erp, 2002, p. 2, Section 2.2).

Relating to the complexity of the signals, the vibrations should use relatively straightforward signals rather than more complex ones, making the recognition of signals easier for the recipients. For example, a study by Gomes et al. (2020) has shown that the recognition of signal cue changes was lower for more complex vibrotactile signals than for simpler signal cues. The authors argue that signals in safety-critical domains should have low complexity (p. 653). To keep the vibration signals relatively simple, more complex gradations of intensities within a signal should not be utilized.

Thunberg and Osvalder (2007) have presented several design guidelines of alarm systems for the "operation of complex process control settings" (p. 85), as used, i.e., in the power generation industry. The authors discussed the recommendations proposed by the *Engineering Equipment and Materials Users' Association* (EEMUA), which are listed in the columns "Characteristic" and "Meaning" in Table 7. The characteristics are then mapped to the design of a vibrotactile hazard warning wearable (column "Vibrotactile Warning Design", same table).

Table 7: Characteristics of Vibrotactile Warning Design

Characteristic	**Meaning**	**Vibrotactile Warning Design**
Timely	Present alarm at the right time	When a worker enters a warning field of a hazard
Relevant	No false alarms	Warn only when entered hazard field
Unique	No duplicate of another alarm	Vibrations should not overlay each other
Prioritized	Should help to focus attention	Should shift attention towards hazard direction
Understandable	Speaks operator's language	Vibrations should be easy to interpret: binary design, cue location indicates direction of hazard
Diagnostic and advisory	Indication of alarm cause and what action is required	Vibration means hazard in certain direction, action depends on specific situation
Manageable	Not too many alarms	Depends on number of hazards one is exposed to

Note. Mapping of vibrotactile alarm design to the *characteristics* and *meaning* of individual alarms proposed by EEMUA (1999, as published in Thunberg & Osvalder, 2007)

3.2.3 Modular Structure and Communication Interface

Implementing a controllable vibrotactile belt requires a control unit to start vibration motors. With such an interface, the control unit can then be accessed by external devices and send commands to the control unit (Figure 3.13). This design provides sufficient flexibility as external devices (such as the computer running the VE) can define all vibration parameters and do not have to be set statically in the used microcontroller.

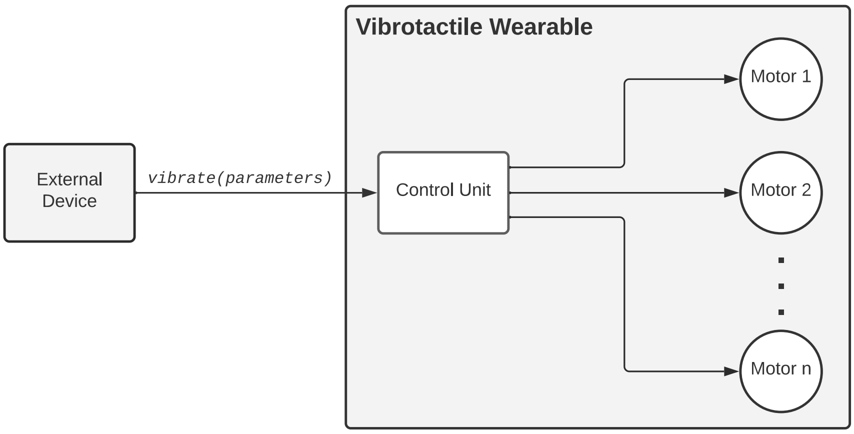

Figure 3.13: Schematic overview of the wearables' interface

This approach also reveals the initial requirements for the control unit. First, the microcontroller should be suitable in size and weight to be mounted on a wearable. Then, depending on the duration of use and the scenario, the energy consumption may be relevant, as the control unit will need some power supply. Depending on the type of vibration motor actuation, it may be necessary to determine whether the control unit permits analog power output of the signal as an option. While digital power output works in a binary manner to start and stop a vibration, analog output also enables control of the power supply to the vibration motor, thus allowing for varying the vibration intensity to implement more complex variations of vibration signals. The computing power of the controller is negligible since the use case to control several vibration motors is less computationally intense.

The control unit must have an adequate interface beyond cable-based communication for external devices (e.g., a computer running the VE or a mobile device). To enable comparisons between virtual settings and their real-world counterparts at a later stage, the wearable and the (external) controlling device should function autonomously and allow wireless communication.

3.2.4 External Controller and Data Logging

The wearable's interface design (as receiver) allows flexibility in the choice of the external sender device, as schematically outlined in Figure 3.13. Thus, with communication via a wireless channel, the wearable can be used in stationary and mobile settings. A wireless signal transmission protocol should be preferred to ensure that testing is also possible in mobile settings, although both options, i.e., via cable, are possible with modern microcontrollers.

By omitting complex logic on the wearable, an external device must also implement functions for performing vibrations pre-test, starting and ending study sessions, and monitoring vibration signals during studies. Pre-testing vibrations are needed to check the functionality of all vibration directions once at the beginning of studies with participants. In contrast, monitoring is needed to ensure each component works properly during study sessions. With this design, it is possible, for example, to use the vibration belt in field studies via smartphones or access it via stationary VR hardware.

Due to the design choice, data logging must also run on external devices. Microcontrollers usually come with limited space, and data handling would include adding logic to the controller and attaching some external data storage to save study data (i.e., external data storage). Thus, the external devices need to implement logging of events from firing signals and logging of acknowledging signals.

3.2.5 Summary of Requirements for Vibrotactile Wearables

To conclude, the requirements from the previous sections on vibrotactile wearables are listed here in Table 9. The requirements focus mainly on wearability, the vibrotactile warnings, their application, and the functioning of this component.

Table 8: Requirements for vibrotactile wearables

ID	Requirement:	Origin
REQ VIB 1	Warnings should be possible for cardinal directions: front, back, left, right	3.2.1
REQ VIB 2	The wearable should be comfortable to wear and remain lightweight	3.2.1
REQ VIB 3	The wearable should be unobtrusive for most movements	3.2.1
REQ VIB 4	The wearable should fit different body sizes	3.2.1
REQ VIB 5	Vibrotactile warnings should be timely, relevant, unique, diagnostic and advisory, and manageable	3.2.2
REQ VIB 6	It should be possible to control vibration parameters separately (vibration area, duration of pulses and pauses, intensity, and repetition)	3.2.2
REQ VIB 7	The meaning of vibration warnings should have a low complexity for safety-critical domains	3.2.2
REQ VIB 8	The wearable requires a power source to function autarkically	3.2.3
REQ VIB 9	The control unit of the wearable should allow for wireless communication	3.2.3
REQ VIB 10	External devices should be able to define each vibration parameter of the wearable	3.2.3
REQ VIB 11	To support mobile and stationary testing an external device should allow logging and monitoring communication of the wearable	3.2.4
REQ VIB 12	To ensure that the vibration motors are working properly, it should be possible to verify their function separately before a study session	3.2.4

3.3 Design and Modeling of Virtual Construction Environments

As discussed in Section 2.3.1, several design aspects must be considered when designing for VR, such as immersion and presence, the locomotion technique, and multimodal perception. The VR experience needs a certain amount of coherence in all relevant modules, e.g., the visual setting, the audio, the dynamics, and the task. In addition, challenges such as ergonomics, comfort, motion sickness, or similar must be considered. VR headsets and controllers offer new interaction possibilities compared to conventional PCs. Thus, acceptable usability is required. The interaction possibilities of the VR systems should be mapped concerning the activities of the domain to implement realistic and practical tasks of the respective domain.

3.3.1 Environmental Design and Presence

The VE should visually and auditorily resemble a real, actual construction environment, to allow a high degree of presence, i.e., the feeling of being on site. To what extent high-end graphics are needed remains to be examined. However, to increase the subjective presence, the choice of typical construction site assets should give participants subjectively the feeling to interact in a construction site environment, and the environment should be interpreted as such (place illusion and plausibility, see

Section 2.3.1.2). For future applications, such models of construction sites could possibly be extracted from existing BIM processes, as discussed in sections 2.3.3 and 3.1.5. Using appropriate audio to resemble a construction site soundscape should support the subjective feeling of being present on the site.

Regarding hazards, ethical aspects should also be considered, and participants should not be exposed to overly dangerous situations. The depiction of accidents or the like should also be avoided. Instead, near-accidents are implemented. Near-accidents (or near-misses) depict certain situations where chances for an accident are increased, for instance, due to missing safety measures, but no accident occurs. Such situations would include a lack of fall protection, open power sources, or walking into the work area of other workers. Based on the contextual factors presented in Section 3.1, different hazards should be implemented.

3.3.2 Task Design

Creating a task for the VE is one of the biggest challenges, as there are several requirements to implement an adequate task design within the VE. First, the task should be related to the context of the domain presented in the VE. In the case of a construction site environment, the task should accordingly have a reference to construction site work. Additionally, the proximity warnings use case defines that a site worker must perform the task on the ground and walk across the site or by a worker driving a construction vehicle (Section 3.1.4).

Due to the interaction with VR hardware, i.e., the use of controllers, it must be considered how the tasks can be 'translated' into a version that works adequately in VR. Mapping the VR controls toward natural interactions involves considering the interaction with virtual objects and how participants can move around the construction site over longer distances. Thus, the task design must consider an appropriate locomotion technique in VR. In addition, the selected task should demand sufficient mental workload to emulate the workload found on worksites without overwhelming participants. Due to the challenges presented, the task design is reconsidered iteratively over the studies.

3.3.3 Communication with Wearables

Implementing a suitable interface to issue warnings from the VR environment toward the wearable is necessary. Events triggered by the VR environment (in case of an occurring hazard) must be transmitted and processed by the interface to execute the warning with specified parameters. The same wireless interface should be used to support real-world mobile settings for comparing evaluation studies between the real-world and virtual worlds. It is possible to communicate with the wearable from inside the VE or any other device that implements the same interface.

Game engines like *Unity*[12] or *Unreal*[13] allow to define certain trigger events via their event system, which serve as the starting point of the warning. For example, as soon as an object runs into the range of a trigger area, an event is fired and can be processed accordingly. In the case of warnings, the event should trigger a vibration on the wearable, with correspondingly defined parameters. Thus, it is necessary that the hazard direction in a virtual environment automatically triggers the corresponding vibration motor in the wearable. I.e., if the danger approaches from the right side, the right side of the wearable must vibrate accordingly. To notify participants in all directions, at least the directions right, left, front, and back should be implemented.

3.3.4 Locomotion

In Section 2.3.1.4, several different ways were presented on how to enable locomotion in VR. For example, teleportation is one of the most commonly used locomotion techniques, but it is unsuitable for the use case of work safety. In construction site settings, hazards can appear suddenly in or off the view field of workers while they walk toward a destination. Due to the teleportation jumps, teleportation might lead to skipping these suddenly appearing hazards. Instead, a continuous movement should be used for such scenarios. Thus, suitable continuous locomotion techniques include real walking, controller-based locomotion, or walking-in-place.

The VR environment should also incorporate the fact that participants' physical activity might influence tactile perception (see Section 2.2.2) and, therefore, evaluate differences between free movement and controller-based locomotion for an informed design decision.

3.3.5 Questionnaires and Data Logging in VR

VR-based testing allows logging all possible actions and interactions and gaze or eye tracking. Data logging should include the VR simulation's start and end time to evaluate the participants' task completion time. For the analysis of participants' reactions toward hazards and warnings, data logging should include a timestamp of when a participant entered the field of a hazard and how long the participant needed to acknowledge the signal with a reaction. Indications about participants' cognitive load can be tested via a stimulus-reaction task. In addition, questionnaires that assess the workload and mental stress should be used to compare the results of the reaction times with the subjectively felt workload.

However, research has shown that using questionnaires in VR is promising to reduce overall study time (Section 2.3.1.2). Questionnaires should be applied in pencil and paper versions to reduce the time of VR exposure and thus reduce the probability of motion sickness symptoms in the participants from long VR exposure.

[12] Unity Technologies: https://unity.com/

[13] Epic Games, Inc.: https://www.unrealengine.com/

3.3.6 Health and Safety in the Design of VR

The health aspects of virtual reality often refer mainly to the occurrence of motion sickness symptoms. VR exposure should therefore be kept to a minimum to avoid motion sickness symptoms as far as possible. For instance, as described in Section 3.3.5, questionnaires should be applied in pencil and paper versions (or computer versions) to reduce VR exposure time. Another aspect to reduce VR exposure time is the duration of the used VR scenario, which should be kept as long as necessary but also as short as possible.

Then, the visual isolation from the real environment of VR users must be considered for safety aspects. A VR Lab should provide participants with the safety of not getting injured by surrounding objects at all times. Therefore, an overview of typical accidents with VR hardware would be necessary, with design instructions on how to avoid these accidents (Section 2.3.1.3).

3.3.7 Summary of Requirements for the VR Laboratory

Finally, based on the theoretical background and the outlining of the design space, several requirements have emerged that should be considered when evaluating *in* and *with* VR laboratories. Requirements are shown in Table 9, each with a cross-reference to the corresponding sections from which the information originates. The requirements are all relevant to implementing a VR Lab but are separated here by components:

Table 9: Overall requirements regarding the laboratory

ID	Requirement:	Origin
REQ LAB 1	The VR scenario should provide a high degree of presence	3.3.1
REQ LAB 2	The VR laboratory should be able to integrate and (re-)use 3D-models from BIM as VE	3.3.1
REQ LAB 3	Test scenarios should be ethical and not cause anxiety in participants	3.3.1
REQ LAB 4	Tasks in VR should relate to tasks in the contextual environment of the domain	3.3.2
REQ LAB 5	When testing use cases, real-world conditions should be replicated in VR	3.3.2
REQ LAB 6	Tasks should demand mental workload without overwhelming participants	3.3.2
REQ LAB 7	Components in the VR laboratory should communicate wirelessly, thus, enabling mobile testing	3.3.3
REQ LAB 8	Events in the VE should be transmitted to external wearables	3.3.3
REQ LAB 9	Hazard directions in the VE need to be mapped to the warning directions in the wearable	3.3.3
REQ LAB 10	It should be tested if and how participants' physical activity influences tactile perception	3.3.4
REQ LAB 11	A, for the research purpose, suitable locomotion technique should be implemented	3.3.4
REQ LAB 12	All relevant behavioral data should be logged within VR and screen recording should be used	
REQ LAB 13	Logging should be done only for data necessary for the research question(s)	3.3.5
REQ LAB 14	VR-exposure should be kept as short as possible	3.3.5; 3.3.6
REQ LAB 15	Relevant safety issues with VR should be identified and prevented	3.3.6

4 Cognitive Workload and Tactile Perception in Virtual Reality

This chapter[14] focuses on examining an *appropriate* VR locomotion technique for the evaluation of vibrotactile warnings. As tactile perception may differ during physical activity (Section 2.2.2) and controller-based locomotion techniques does not require to move around physically (Section 2.3.1.4), it is necessary to understand the impact of different locomotion techniques on tactile perception. Two studies are presented that investigate the impact of VR locomotion techniques on cognitive load and the recognition of tactile warning cues. As walking leads to a reduced tactile sensitivity (cf. Gomes et al., 2020), the studies investigate differences between walking or static positions.

4.1 Research Objectives

The first study in Section 4.2 investigates the detection of vibrotactile cues in VR. It focuses on comparing tactile perception during (real) walking in VR and a real environment. As shown in Section 2.3.1, some techniques enable movements using less (real) motion than others. For instance, using a controller's touchpad or joystick does not require body movements. This study uses a Choice Reaction Time (CRT) task to investigate detecting and recognizing vibrotactile cues and compares how vibrations are perceived in both reality and VR.

Real walking in VR is mainly limited to a certain physical space ('room-scale VR') by either the hardware or the research environment, i.e., a laboratory. In contrast, controller-based locomotion can serve as a locomotion technique to experience larger VEs. However, detecting vibrotactile cues might be more challenging when physically moving than standing still. A second study in Section 4.3 compares both techniques in a solely VR setting.

4.2 Comparison of Real Walking in VR and Real Environments

The purpose of this study is twofold. First, its objective is to analyze whether and how physical locomotion affects the detection of vibrotactile stimuli compared to static

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[14] Contents of this chapter have been published in:

Jelonek, M., Trost, L., & Herrmann, T. (2022). A Vibrotactile Reaction Time Task to Measure Cognitive Performance in Virtual and Real Environments. In J. Y. C. Chen & G. Fragomeni (Eds.), Virtual, Augmented and Mixed Reality: Design and Development (Part I): Vol. LNCS 13317. Springer.

postures in which participants concentrate fully on the vibration task (as a 'baseline' measure) between real environments and in VR. Second, the study is designed in an exploratory nature to investigate the technical artifacts needed, their usability, and the mobile evaluation setting: semi-structured interviews of the participants will be used to investigate how well the vibrotactile stimuli are perceived via a vibrotactile belt, how the virtual environment is received and which factors in it still need to be changed, and whether the implemented dual task requires sufficient cognitive effort.

4.2.1 Study Design and Choice-Reaction Time Task

For the study, a within-subject design with four conditions was used. Participants had to do a CRT task (Figure 4.1) while standing still and solely concentrating on the vibrations (conditions 'static-Real' and 'static-VR') and while moving in the real world ('move-Real') as well as in VR ('move-VR'). During each condition, the reaction times to the CRT task were measured. CRT tasks build on the stimulus-response phenomena to explore the psychological factors of human beings while they must respond to multiple stimuli. The CRT was used here to investigate how fast participants react to vibrations in the four directions.

For the task, 40 cues (trials) were presented to the participants via a belt around the waist, ten cues for each cardinal direction: left, right, front, and back. The cardinal directions were used as a prototype regarding directional warning cues that would indicate to participants the direction of a hazard. The time between cues and the direction of the following cue were randomized to prevent any anticipation of signals. Additionally, logging included every signal given and participants' responses (time and direction) to investigate participants' accuracy. To minimize a bias of learning effects in the results, the sequence of conditions was counterbalanced, and participants were randomly assigned to each sequence.

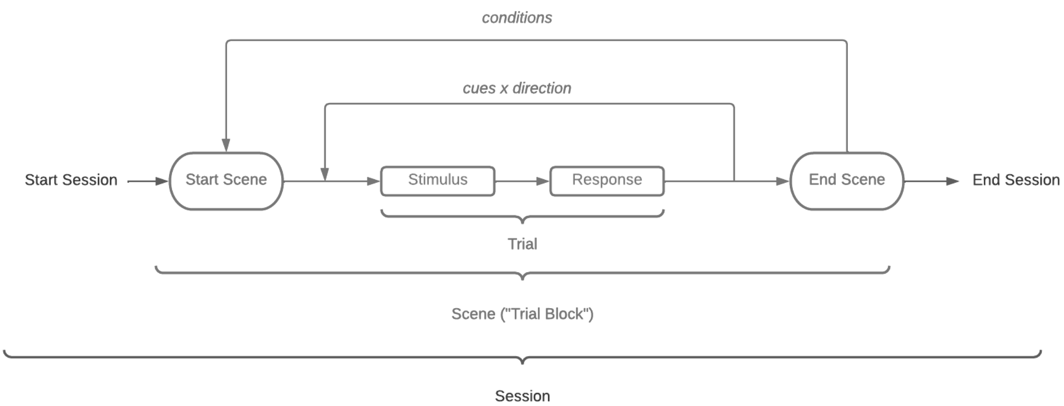

Figure 4.1: Schematic overview of the CRT Task

4.2.1.1 Measures and Variables

A mix of qualitative and quantitative data collection was used. To obtain information about the participants, a short demographic questionnaire was used (Appendix E).

Questions included age, occupation, and prior experience with VR. To compare the task workload for each condition, participants' subjective workload was assessed with the Nasa Task Load Index (Nasa-TLX). The TLX consists of six scales, measuring the mental demand, physical demand, temporal demand, performance, effort, and frustration. It is administered as '*Raw-TLX*', without the subjective weighting of subscales (Appendix F). In addition to the TLX, participants' reaction times (RT) were measured, as well as the times participants did not respond to vibrotactile cues, responded incorrectly to vibrotactile cues by misinterpreted the direction of cue occurrence.

To evaluate the sense of presence of the VR environment, the *iGroup Presence Questionnaire* (iPQ) was used (Appendix G). The iPQ uses three subscales, measuring the spatial presence, the involvement, and the experienced realism in the virtual scene. Additionally, one item assesses general "sense of being there" (Schubert et al., 2001).

Furthermore, observations were made and documented during the study, about how well the participants were able to handle the VR hardware and what problems they might have encountered during the process. At the end of each session, a semi-structured interview was conducted with each participant. Contents of the interview included the usability of the system, questions about the vibration belt and the vibrations, and the virtual environment (for the interview guideline, see Appendix C). Based on the study design, the independent variables were *physical activity* (standing and moving), *environment* (reality and VR) and *vibration direction* (front, left, rear, right). The vibrations were applied with full intensity (see next Section 4.2.1.2). The dependent variables are reaction times and accuracy (error rate) to the vibrotactile stimuli and their direction.

4.2.1.2 Vibrotactile Belt and Mobile Apparatus

A belt was designed to apply the CRT via vibrotactile cues using an ESP32 NodeMCU microcontroller and eight coin-vibration motors (3x10mm, 3V, 11000 RPM). Two vibration motors were attached to each side on the left, front, right, and back (Figure 4.2 and Figure 4.4). The decision to use two motors was based on the subjective perception during prototyping that the signal of one motor could have been too weak to be noticed. The CRT task was implemented on a smartphone application, which was used to start and stop the task as well as store participants' data. The use of the smartphone allowed for a mobile evaluation. The belt was connected via cable to an input control with four direction corresponding buttons to react to the directional vibrotactile cues of the CRT task (Figure 4.2).

Figure 4.2: Abdominal (waist) belt with vibration motors and the input control

The system used Wi-Fi for wireless communication between the wearable and the smartphone to ensure flexible use in mobile scenarios. The smartphone worked as a mobile Wi-Fi hotspot for the microcontroller. When a trial block began, the mobile application sent randomized signals to the belt. When an input button was pressed, a signal was then sent back to the smartphone. Timeouts were logged whenever participants did not respond five seconds after the vibration was given.

4.2.1.3 Virtual Environment and Task Design

For the VR conditions, a VE was designed that visually and auditorily resembled a construction site setting. For the visual design, typical construction site 3D assets were used to model the scene, while the environment's soundscape used an audio recording of an actual construction site. Limited by the constraints of the (physical) seminar room in the university, the interaction area inside the VE allowed participants to move freely on a rectangular field of around 4.1m x 3.2m (see Figure 4.3). The field had to be smaller than the actual room size to prevent participants from accidentally colliding with the walls or other objects in the room. However, when participants came too close to the edge of the interaction area, a red grid ("*chaperone*", see Section 2.3.1.3) was displayed in their field of view. The HTC Vive Pro Eye was used (wirelessly) in this study.

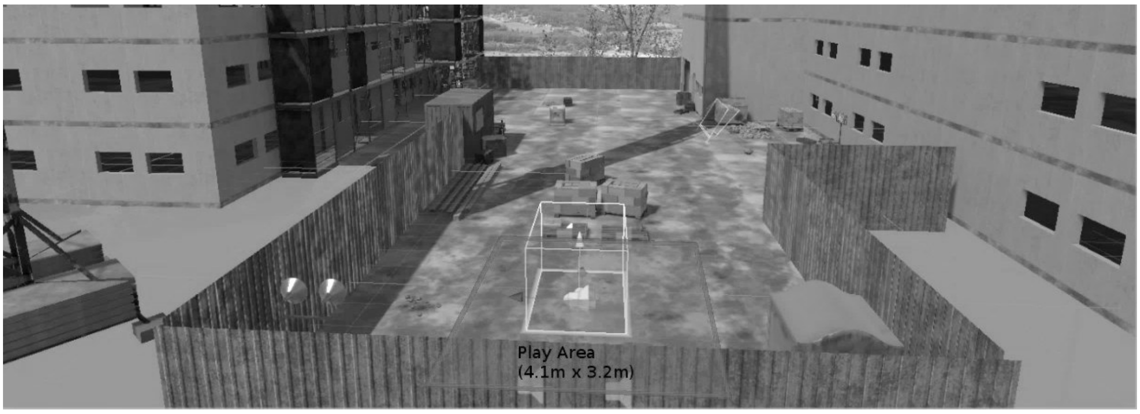

Figure 4.3: Virtual Environment used in the first Study

Note. The red marked area shows the play area in which participants could move freely.

For the task, participants had to move around and sort two types of cement bags from one side of the play area to the other. Two wooden pallets were placed at the end of each side. On one side were pallets with mixed cement bags (red and blue), whereas on the other side, two pallets were placed, each with one cement bag indicating the color for the sorting task (Figure 4.4b).

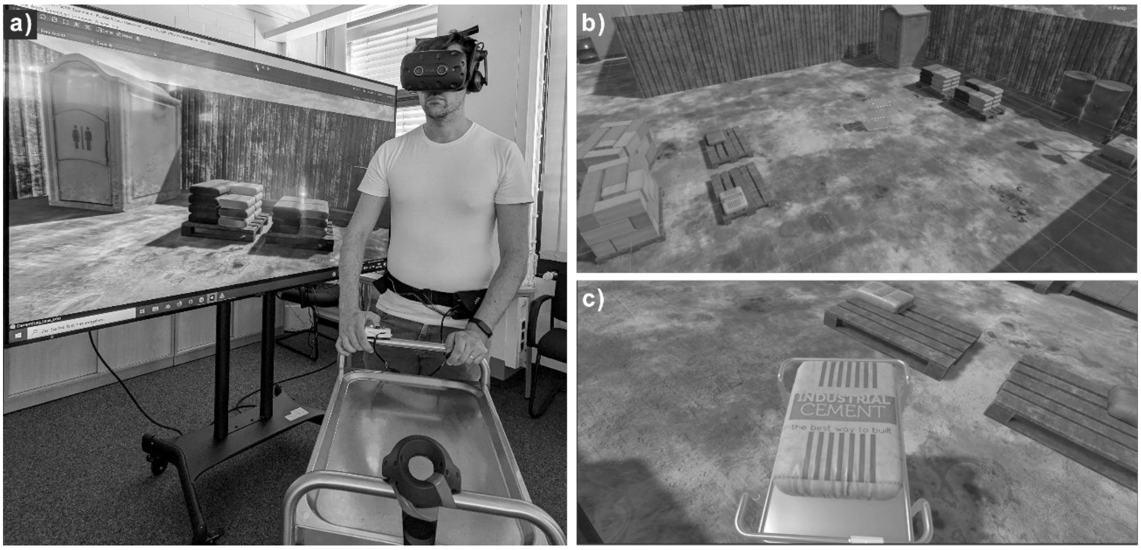

Figure 4.4: Serving cart prototype that was tracked inside the virtual environment

Moving the serving cart to a pallet automatically picked up the cement bags and placed them down when reaching the pallets on the other side of the interaction area. This task was chosen to ensure participants had to physically move around the room without needing to interact with the VR controllers. They used a serving cart as a 'transporting tool', with a Vive Controller attached to track the real cart inside the room and to update its digital counterpart in the VE accordingly (see Figure 4.4). The cardboard with the input buttons of the vibrotactile belt was also attached to the cart, allowing participants to move around while responding to the CRT task.

As soon as participants were directly in front of the (virtual) wooden pallets, an event triggered to either load or unload a cement bag. The cement bags had to be sorted by color, meaning participants had to decide to which pallet they had to bring their current bag, to increase the cognitive demand by a minimum (Figure 4.4c). For the task in the real environment, participants were asked to move the serving cart through the corridor of the university building.

4.2.2 Research Method

To investigate whether the detection of vibrotactile cues is comparable during a VR experience to a real-world setting, a CRT was used to measure and compare participants' reaction times. As described in Section 2.1.4, RT measurements are sensitive to detecting variations in cognitive efficiency and performance (cf. Cinaz et al., 2011).

The study is based on four conditions: standing or moving in the real world (‘static-Real’, ‘move-Real’) or VR (‘static-VR’, ‘move-VR’). During the *move*-conditions, participants had to fulfill the simple transporting task, as such tasks may occur in various jobs (e.g., logistics, warehouses). In the real setting, participants transported a box with the serving cart on a planned route on a floor inside a university building. In the static conditions, participants stood still and did only the CRT as baseline measures. The difference in the static conditions was that in the static-VR condition, participants wore the VR headset while experiencing a neutral VR environment. In contrast, they stood in the laboratory room without the VR headset in the static-R condition.

Participants wore the vibrotactile belt around their waist during the study (see Section 4.2.1.2). The belt assigned cues randomly in four directions: front, left, right, and back. Whenever a vibration cue was given, participants had to react as fast as possible by pushing a button for the matching direction of the cue. An exploratory data analysis should provide insights into how the RTs differ between the four conditions and if specific directions were perceived more accurately than others. Considering tactile suppression and reduced tactile sensitivity during physical activity, the RTs should be longer for conditions where participants move than in static ones.

4.2.2.1 Procedure

Before the study, participants were introduced to the overall system and the task before handing out the informed consent and a short questionnaire with demographic questions. To ensure that participants understood the tasks, they fulfilled a short trial beforehand and had the chance to experience the vibrations applied via the wearable. After that, participants started with either of the conditions. The order of conditions was counterbalanced between participants. After each condition, participants completed the Nasa-TLX. For the VR conditions, they also completed the iPQ. When all four conditions were completed successfully, a semi-structured interview was conducted with each participant, and they were thanked for their participation.

4.2.2.2 Participant Sample

After two prior test runs of the study to find any bugs or arising challenges, a total of twelve participants[15] (10 male, 2 female) took part in the study with a mean age of 24.33 (*SD* = 3.14). Six participants mentioned they already had a lot of experience with VR, whereas the other six participants stated they had none or only very few prior experiences. Due to an unnoticed technical issue on one day of the study, four CRT data sets had to be withdrawn from the data as partly or totally corrupt, leaving a resulting data set of 8 participants (7 male, 1 female) for the CRT data with a mean age of 23.5 years (*SD* = 1.22). However, the interviews of all participants were considered for the qualitative analysis, as every participant had experienced all four conditions, and their comments could uncover relevant aspects, even when their CRT data was not usable for the quantitative analysis.

4.2.2.3 Safety and Ethics

Prior to the study, an informed consent was handed out, and the study was explained to the participants. They were given the chance to ask questions at any time during the study and were also informed that they could stop and withdraw their participation at any time, especially as soon as signs of motion sickness appeared. For hygiene reasons, the VR headset was covered with a disposable hygiene cover for each participant.

4.2.3 Results

For the data analysis, first, the RT data of the dual-task was compared between the four conditions. Second, the accuracy and error rate of participants' responses were calculated. Third, the (raw) Nasa-TLX questionnaire scores were determined and compared across conditions. Fourth, the results of the iPQ questionnaire were calculated and enriched with the comments from the interviews to evaluate the VE used in this study. If not disclosed otherwise, *R 4.1.2* was used for the data analysis. Finally, the interviews were analyzed to all relevant aspects that participants mentioned during these interviews.

4.2.3.1 Choice Reaction Times Analysis

Prior to the analysis of RTs, the collected data set of eight participants (total of 1280 RTs) was sanitized by the following procedure: First, the data set was filtered for responses to a vibration cue, removing rows where participants did not react (timeouts), leaving a set of 1246 RTs. Second, the data set was filtered for the correct response to the given stimulus direction, removing data where participants reacted to a stimulus but chose the wrong input direction, leaving a data set of 1088 responses. Third, the data for each condition was filtered by excluding RTs that were slower than two standard deviations

[15] An a priori power analysis with G*Power for required sample size in this test design suggested a minimum sample size of n = 16 for a power of 0.8 (1-β error probability), using α = .05, two conditions, two measurements, and an effect size f = 0.4.

above the mean in each condition as well as RTs that were faster than 200ms (cf. Harald Baayen & Milin, 2010; Whelan, 2008). Due to this process, the final data set was reduced to 1044 RTs. An overview of the means for each condition is shown in Table 10.

Table 10: Descriptive statistics of the Choice Reaction Time (CRT) Task.

Condition	RTs (Total)	Mean (ms)	Std. Dev.
Static-Real	265	633.19	132.36
Static-VR	282	632.26	116.34
Move-Real	239	915.01	220.16
Move-VR	258	914.47	192.42
All	1044	766.97	219.37

The descriptive data exploration has shown that participant's mean RTs were faster in the static conditions compared to the RTs in the conditions with physical movements. Furthermore, the exploration of the dataset via a kernel density plot showed that RTs in the move conditions are more widely distributed compared to the static conditions (see Figure 4.5).

For the further analysis, the mean RT for each participant was calculated for each condition, leaving 32 data rows (8 participants x 4 conditions). The data was checked for outliers. QQ-Plots and a Shapiro-Wilk test both suggested that the assumption of normality was met. To compare the differences in RT, a two-way repeated-measures analysis of variance (ANOVA) was conducted in SPSS 28 with the factor *activity* ('static', 'move') and *visual* ('VR', 'real').

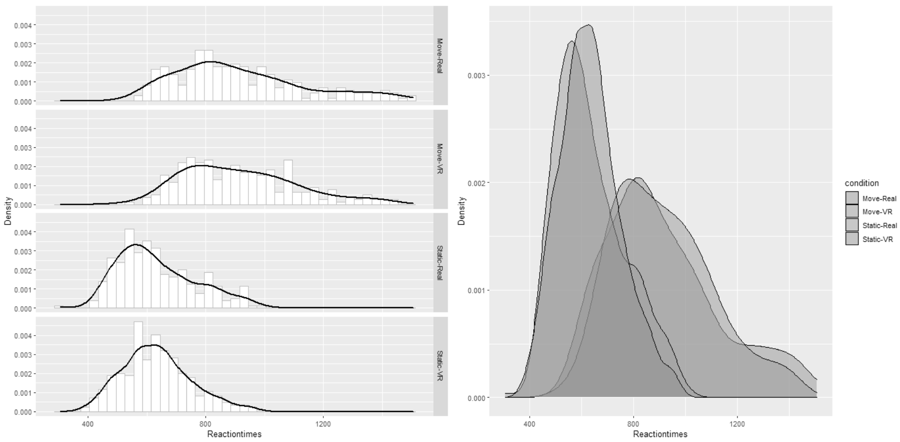

Figure 4.5: Kernel density plots of the RT data

The two-way repeated measures ANOVA revealed that there was a significant main effect on the RTs based on the activity of participants, $F(1,7) = 142.78$, $p < .001$, $\eta^2 = .953$, indicating that the RTs of participants were significantly faster when standing still compared to walking conditions. Regarding the visual condition, the ANOVA showed no significant effect on the mean RTs for VR and non-VR, $F(1,7) = 0.009$, $p = .927$, indicating no differences in mean RTs based on the visual surroundings. There was no significant interaction effect between the movement type and the visual surroundings on the participant's mean reaction times, $F(1,7) = 0.004$, $p = .949$. A Bonferroni adjusted posthoc pairwise analysis revealed that based on participant's physical activity, participants reacted on average significantly slower during movement $M_{\text{Diff}} = 283.47$, $p < .001$, $CI_{95\%}$ [227.37, 339.57].

4.2.3.2 Vibration Distinctiveness and Error Rates

The accuracy of RTs was calculated based on the vibrations to which participants did not react at all and which were misinterpreted to evaluate the distinctiveness of the four directions of cues. The exploration of data has shown that for each move-condition only 38 vibration stimuli to the back were noticed with a correct response, compared to 80 given (10 per participant). In percentage, only 47.5% of cues applied to the back were interpreted correctly.

The analysis of reactions is considered on two levels: for the conditions (Table 11) and the vibration directions (Table 12). The data shows that the vibrations among the conditions were generally well detected (the lowest score for reactions on vibrations was 94.69% for static-R). However, it is also visible that detecting the correct direction of vibrations was lower (between 78.44% - 91.88%).

Table 11: Accuracy during the CRT Task per condition.

Condition	Reaction to vibration	Correct response to vibration
Static-R	94.69 %	85.94 %
Static-VR	99.69 %	91.88 %
Move-R	97.50 %	78.44 %
Move-VR	97.50 %	83.75 %

When examining the RTs per direction, the data reveals the lowest correct responses for the vibrations applied to the back. Whereas the overall reaction to vibration ratio was above 95%, the correct response to vibration cues was especially limited when the vibration signal was given in the back (only 66.25% correct responses).

Table 12: Accuracy during CRT Task per cue direction.

Cue Direction	Reaction to vibration	Correct response to vibration
Back	98.13 %	66.25 %
Front	95.63 %	88.13 %
Left	98.44 %	94.06 %
Right	97.19 %	91.56 %

During the semi-structured interviews, participants stated that, in total, the vibration signals were noticeable in most cases but should be applied with a higher intensity. Specifically, participants mentioned that the vibration cues on the back were the most difficult to detect. The collected data supports this statement, as the percentage of not responding to a stimulus is generally low. In addition, when considering the conditions, the misinterpretation of the vibrotactile cues indicates that participants found it slightly more challenging to interpret the correct direction of a signal during movement.

4.2.3.3 Workload and Task Difficulty

Generally, participants stated during the interviews that they perceived the workload as low for all conditions, but that it was slightly higher when moving (move-Real and move-VR). The overall TLX results (Table 13) reveal that the mean workload was higher for the move conditions than the static ones (*M* = 32.01 for move-Real); *M* = 29.86 for move-VR; *M* = 15.83 for static-Real; *M* = 14.88 for static-VR). Additionally, the mental demand subscale of the TLX results show that participants' mean mental demand was higher in the move-R (*M* = 36.67) and move-VR (*M* = 27.16) conditions than in the static-R (*M* = 13.33) or static-VR (*M* = 16.67) ones.

Table 13: Mean and standard deviations for the TLX ratings

	Static Real		**Static VR**		**Move Real**		**Move VR**	
Scale	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Mental	13.33	16.42	16.67	12.49	36.67	26.14	36.67	27.16
Physical	6.25	5.28	7.92	9.64	28.33	24.71	22.92	19.12
Temporal	20.42	23.50	15.92	21.45	23.33	22.39	25.83	24.11
Performance	16.67	8.62	21.25	14.32	40.42	21.79	34.17	17.30
Effort	16.67	19.11	17.08	21.16	38.33	24.15	32.92	23.11
Frustration	21.67	19.35	10.42	19.48	25.00	23.45	26.67	26.83
Workload	15.83	16.85	14.88	17.02	32.01	23.94	29.86	22.95

A non-parametric Friedman test on workload was conducted (Figure 4.6). The test has shown statistically significant differences in perceived workload, $X^2(3) = 26.8$, $p < .0001$, $W = .74$. Pairwise post-hoc Wilcoxon-Signed Rank tests with a Bonferroni correction have shown statistically significant differences between the static and move conditions: static-Real to move-Real ($p = .003$), static-Real to move-VR ($p = .003$), static-VR to move-Real ($p = .003$), and finally static-VR to move-VR ($p = .038$). No statistically significant differences were found between both static conditions, and also not between both move conditions.

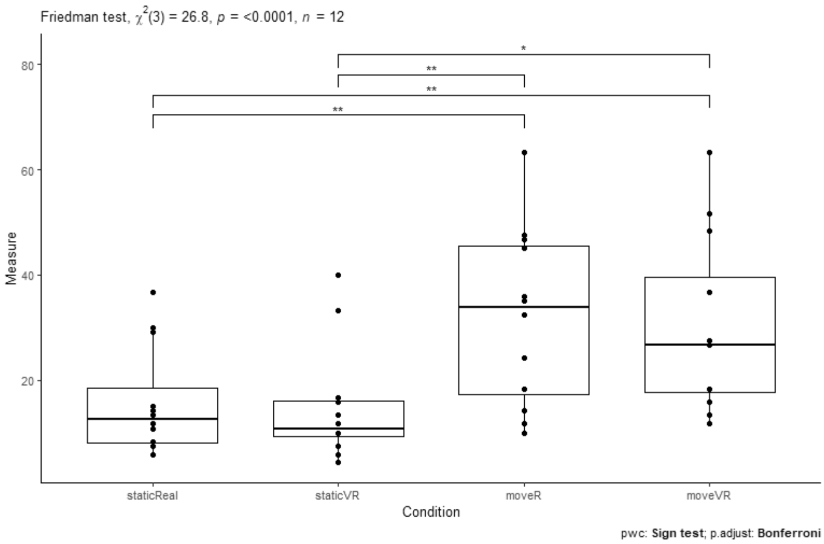

Figure 4.6: Results of the Friedman test on the overall workload

4.2.3.4 Virtual Environment and Presence

Regarding the VR settings, the subjective presence assessed by the iPQ for both VR settings was compared, the neutral VE (static-VR) and the construction site setting (move-VR). The iPQ allows to assess the general felt presence (GP), the spatial presence (SP), the involvement in the scene (INV), and the experienced Realism (REAL). All items of the iPQ range from 0-6.

The iPQ data has shown that the GP was rated higher for move-VR (*M* = 4.5) than for static-VR (*M* = 3.75). The lowest values were found for the experienced realism (*M* = 3.1 for move-VR; *M* = 2.35 for static-VR). A bar plot of the data displaying with standard deviation is shown in Figure 4.7.

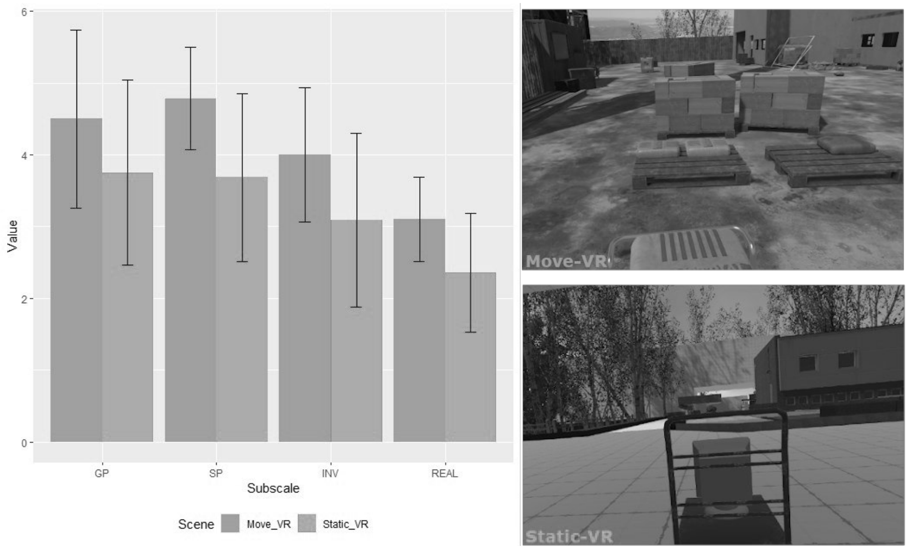

Figure 4.7: iPQ Results for Static-VR and Move-VR

In the interviews, most participants found the task in the move-VR condition simple but realistic enough for the context of construction sites. However, one participant stated that he found the spawning of cement bags on the palette or serving cart unrealistic. For a more realistic feeling, the participant mentioned ideas to lift tracked physical objects or that an animated construction worker avatar could put the bags on the cart. All participants stated they would have liked a more complex task and interaction in the simulation.

In general, participants considered the look of the construction site environment in move-VR as realistic. However, about half of the participants mentioned that they would have liked more dynamics in the scene, such as construction workers or moving vehicles. Some even mentioned that the sound in the environment did not match the scene, as one could to hear construction vehicles, although there were none in the scene. The other participants mentioned they focused so much on the task that more dynamics would have distracted them, although the cognitive workload was rated relatively low. Besides more dynamics, one participant with prior knowledge of VR complained about the virtual environment's graphics and would have liked a more realistic one. Overall, the interview statements showed that the dynamics in the scenario should be substantially increased. With more dynamics, the degree of experienced realism and participants' cognitive effort would increase by adding more distracting objects to the scene.

Considering the serving cart, which was chosen mainly for pragmatic reasons (e.g., a handlebar to fixate the input unit, see Figure 4.4), no participant complained about the serving cart a construction site setting. Only when directly questioned by the interviewer did participants realize that one would usually use, for example, a wheelbarrow or some other tool. Several participants confirmed they were so focused on the task that they did not think about the serving cart, but all confirmed afterward that it is no tool that one would find on construction sites. Additionally, several participants (with and without prior VR experience) mentioned that they were surprised at how well the location tracking of the physical trolley worked in VR. Apart from the construction scenario, one participant with prior experience working in logistics found the serving cart as perfect tool for VR scenarios in logistic halls.

Regarding the locomotion technique, every participant positively highlighted the experience of moving freely in VR, even if tracking was limited to a certain area, and that it made the VR experience more realistic and interactive. Participants generally stated that real walking in VR added to the feeling of being in the scene. When asked if they did not feel uncomfortable moving freely in space, all participants stated that the real serving cart was sufficient support and that it felt natural to move. In addition, the participants stated that the chaperone provided sufficient safety not to run into walls. However, the perceived safety can be different when moving freely in VR without an additional cart being held in front.

4.2.3.5 Health Related Observations

Before the experiment, one participant warned the study facilitator that motion sickness symptoms occurred every time he tried out VR. This participant confirmed that he had not experienced motion sickness symptoms during this experiment. Apart from that, no other participant experienced motion sickness during the experiment.

Another participant contacted the author months later and said she would now wear glasses. During the post-play interview of this study, this participant criticized that the image in the VR headset and some objects appeared slightly blurry. As a result of the study and the exchange with the study facilitator during the interview, the participant went to the optometrist and was diagnosed with mild myopia.

4.2.4 Discussion

The results of this study have shown that physical movement significantly increases reaction times on vibrotactile cues, which supports findings from literature (e.g., Karuei et al., 2011). As there were no significant differences in reaction times between VR and the real environment, the results suggest that the visual condition does not impact detecting and reacting to vibrotactile cues. This result supports findings in the literature that being immersed in a VE using a VR HMD does not increase mental effort compared to real environments (Luong et al., 2019). Thus, the results suggest that with real walking, VR is a valid method to study vibrotactile feedback.

However, participants had difficulty detecting the correct direction of a vibration cue, with only 66.25% of correct responses to vibrations applied to the back. This result can have two explanations: either the participants noticed the directions but could not attribute them to the correct direction, or they made errors via the input buttons. During the interviews, several participants expressed that they had noticed the vibration but were unsure which direction it was coming from, as they could not distinguish it from others.

The results of the study also inform the design process of the vibrotactile wearable, the virtual environment, and the task design. Regarding the vibration intensity, the qualitative and quantitative data showed that vibrations were not reliably detected, especially at the back. In addition, participants expressed the desire for a higher intensity of vibrations to distinguish the directions from each other. Thus, slightly larger vibration motors should be considered to increase the intensity (Section 2.2.3).

The task for the study was rated as relatively simple, although it was understood as plausible for the construction domain. Here, interview statements confirmed data from the TLX questionnaire. Although the TLX results indicate that the cognitive load was slightly higher during movement, participants regarded the task as too easy and not cognitively demanding. The results indicate that a more complex construction task is needed for follow-up studies. Some participants pointed out that the task seemed unrealistic as they did not have to lift and put away the cement bags by themselves, thus not having to interact with the VE. However, no participant questioned using a serving cart (in VR) on construction sites, as they were focusing so much on the task that they did not question the tool's plausibility.

The VE was generally rated as somewhat realistic, although several participants mentioned that dynamics were missing in the scene, such as moving vehicles or construction workers. The soundscape was rated as realistic but mismatched the VE. Thus, both aspects should be improved to increase the perceived realism of the VE. The iPQ data confirms the statements, as the experienced realism was rated as the lowest, compared to involvement in the scene, spatial presence, and general presence. Participants highlighted the immersion of the VR headset, which explains the higher scores for spatial and general presence. However, participants added that real walking increased the feeling of 'being there'. This observation confirms previous results from the literature (Steinicke et al., 2009; Usoh et al., 1999).

4.2.5 Limitations

In this study, the detection of vibrotactile cues has been tested with a CRT task in four different conditions (standing or moving in either a VR or real-world setting). The results have shown that detecting cues both under motion and while standing still are comparable in VR and reality. However, there are differences in the RTs between movement and standing still. This result is comparable to other research showing that the response time and the error rate to react to vibrotactile signals are higher during physical load (e.g., Cobus et al., 2018).

However, the study has three major limitations:

1) Regarding the statistical calculations, the sample of quantitative data with $n = 8$ is relatively small. Therefore, representative statements are hardly possible. Nevertheless, the results show a strong tendency for RTs to vibrotactile cues to be slower during movements, and the statements of participants as well as the literature support these results.
2) Real walking limits the virtual testing space to the boundaries of the (physical) laboratory space. Thus, a follow-up study should compare other VR locomotion techniques to real walking.
3) The participants' statements regarding the degree of the virtual construction site must be interpreted cautiously, as only one participant had already been on a real construction site.

4.3 Comparing Controller-Based Locomotion and Real Walking in VR

In a follow-up study, the locomotion techniques of controller-based and real walking were compared concerning cognitive effort and detecting vibrotactile cues in VR. In contrast to real walking, controller-based locomotion allows the exploration of open space in VEs. Thus, controller-based locomotion allows to evaluate much larger construction scenarios. However, using the controller for movement might reduce the immersion and felt presence of the VR experience and overload the controller functions inside the VE, as they are then used for interaction with objects and to move around.

4.3.1 Study Design and Reaction Time Task

For this study, a within-subject design was used. Two different locomotion conditions were considered: using controller-touchpads to move (*Controller-VR*) and real walking (room-scale) motion tracking (*Walking-VR*).

The dual-task paradigm was applied to examine differences in the cognitive effort of both locomotion techniques in VR experiences. While participants completed tasks in a VR scene, they also had to respond to a set of randomized vibrotactile cues in five directions during a simple RT task. Three construction tasks were used, which differed in their degree of difficulty (see Table 14). The sequence of conditions was counterbalanced between participants, and the tasks inside the VR experience always followed the same sequence: After doing the baseline RT measure (in VR but without a secondary task), participants started with the task that needed the most controller interaction (wall building), before doing a task that needed slightly less interaction (drilling), and a task with almost none controller interaction (cement mixing).

Table 14: Complexity of VR tasks among both conditions

Task	**Condition and Interaction Complexity**	
	Walking-VR	**Controller-VR**
Baseline	Low (static)	Low (static)
Wall Building	Hard (Interaction)	Hard (Movements + Interaction)
Drilling	Medium (Interaction)	Medium (Movements + Interaction)
Cement Mixing	Low (mostly static)	Low (mostly static)

4.3.1.1 Measures and Variables

An RT task was performed during the VR experience to measure the influence of the locomotion technique on participants' cognitive effort. Accordingly, the locomotion technique and task complexity were considered as independent variables. The RTs and the error rate to vibrotactile cues were considered as dependent variables. After each condition, the usability was assessed with the *System Usability Scale* (SUS), the user experience with the *User Experience Questionnair*e (UEQ), and the workload with the (raw) Nasa-TLX. Due to time constraints, semi-structured interviews were not used. However, the study facilitator wrote down observations and comments by the participants and asked participants questions during the study if something needed to be clarified.

4.3.1.2 Vibrotactile Belt and Apparatus

Based on the results gained from the first study (Section 4.2), the vibrotactile wearable was updated. Changes involved adding more vibration motors to the back, as especially the recognition rate on the back of the participants was lower compared to other directions (see Section 4.2.3.2). Compared to the prior version with eight pancake/coin motors, the updated belt integrates ten cylindric vibration motors (two each for the front, left and right side) to increase the overall vibration intensity. For the back, four vibration motors were used, two on the left side of the back and two on the right side, causing the vibration motors to be positioned at the back muscles and not directly above the spine (Figure 4.8).

Compared to the prior version, the belt used velcro strips to allow higher flexibility in positioning the vibration motors for different body sizes and abdominal circumferences. The motors on the right side could be freely adjusted (Figure 4.8, left), while the motors on the front and left had to be detached and reattached in a new position. The control unit for the vibration motors was a NodeMCU ESP32 microcontroller attached to the back of the belt (Figure 4.8a). Instead of coin vibration motors, larger-sized coreless cylindrical vibration motors were used (3.0V, 7500 RPM). Using the same microcontroller as in the previous study, the belt's control unit was accessible from the VR simulation to the belt via Wi-Fi during runtime. Another change regarded the input mechanism. As this study was intended to be used purely in VR, the button above the touchpad of the VR controller was used as input to react to vibration cues.

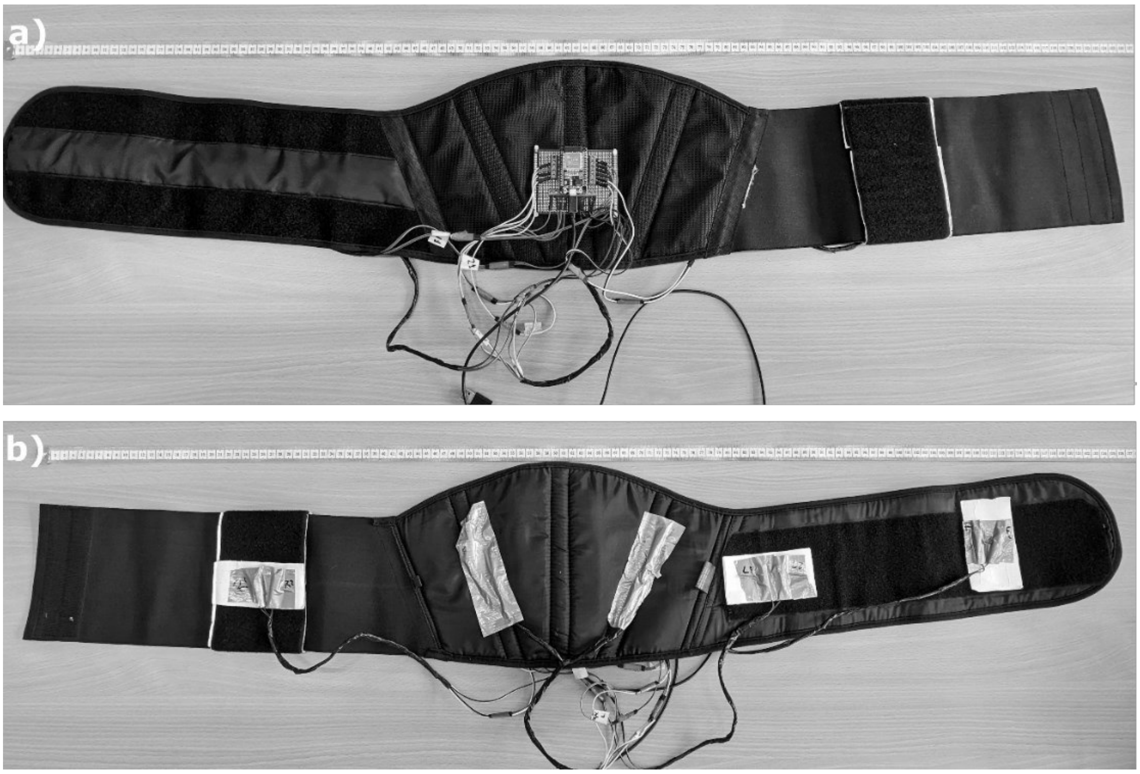

Figure 4.8: Abdominal belt with 10 vibration motors providing directional vibrotactile cues.

4.3.1.3 Virtual Environment and Task Design

Based on feedback from the first study (Section 4.2.4), an updated virtual construction site scene was modeled for the study (Figure 4.9) that included more construction objects and some dynamics (two moving vehicles and two walking workers). The HTC Vive Pro was used wirelessly as hardware, allowing participants to move freely inside the given space. For the motion tracking (real walking) condition, a space of 4x3m was available inside the laboratory.

Figure 4.9: Overview of the virtual construction site in the second study

Inside the VE, participants had to fulfill three tasks:

1) Finishing a brick wall by applying mortar to bricks and adding them to the wall,
2) using a drilling hammer to drill several holes into marked spots on a wall, and
3) holding a cement mixing stick in a pit with cement.

Each task differed in complexity (see Table 14), as different degrees of interaction with the VR world were required to solve the tasks. A tutorial scene was included that participants had to complete before the actual testing to ensure that they could solve the tasks. An overview of the tasks is shown in Figure 4.10:

a) finishing a bricked wall by applying mortar to bricks and adding the bricks to the wall,
b) drilling predefined holes with a drilling machine, and
c) mixing cement.

In the tutorial scene, a shorter version of each task was presented.

Figure 4.10: Used tasks in the VR Scenes, wall building, drilling, and mixing cement

4.3.2 Research Method

The VR Lab was prepared inside a seminar room of the Ruhr University Bochum to conduct the study. The study took place in February 2021. Due to the ongoing COVID-19 pandemic, several safety regulations had to be followed (see Section 4.2.2.3).

4.3.2.1 Procedure

After being welcomed to the laboratory, participants were given an informed consent form for participating in the study and using their data. Then, the overall procedure of the study was explained to the participants. They were informed that the equipment had been disinfected beforehand and that they could terminate their participation at any time, especially if they noticed any motion sickness symptoms.

If no further questions arose, the vibration belt was strapped on the participants, and they were given the VR controllers. Then, the handling of the controllers was explained and described how to hold them optimally to ensure that the button for acknowledging vibrations in the RT task could be pressed without difficulty. After that, participants put on the HMD and the VR experience started with the tutorial scene.

In the tutorial scene, participants were explained the controls again and had a chance to practice. For this purpose, shorter versions of the tasks from the actual test had to be solved in the tutorial to ensure that each participant was able to solve them and that any problems that might have arisen could still be addressed during the tutorial. As shown in Figure 4.11, the tasks were to finish a brick wall by applying mortar to one brick and putting it in the right spot in the wall (a), to drill one hole (b), and to mix cement (c).

Participants could finish the scene by moving towards a door of a construction site container (Figure 4.11c), and were teleported to the actual construction scene (see overview in Figure 4.9). In the scene, participants were asked to stand still and do the baseline RT task (solving the RT task without a secondary task). Participants started either with controller-based locomotion or real walking. In both conditions, they had to walk between jobsites with controller-based movements.

The tasks followed the same sequence as the tutorial: first, participants had to finish building a brick wall, the second task was to drill holes with a drilling hammer, and the last was to mix a pit of cement with a cement mixing stick. During each task, the participants did also an RT task in which eight vibration cues were applied randomly via the belt. The RT tasks started simultaneously with the start of each construction task.

After finishing the last task, participants removed the VR hardware and filled out the (raw) Nasa-TLX, the SUS, and the UEQ. The procedure started then with the other condition. Depending on the observations during the study, the study facilitator asked clarifying questions for observed phenomena during each session. One session took around 1:15h.

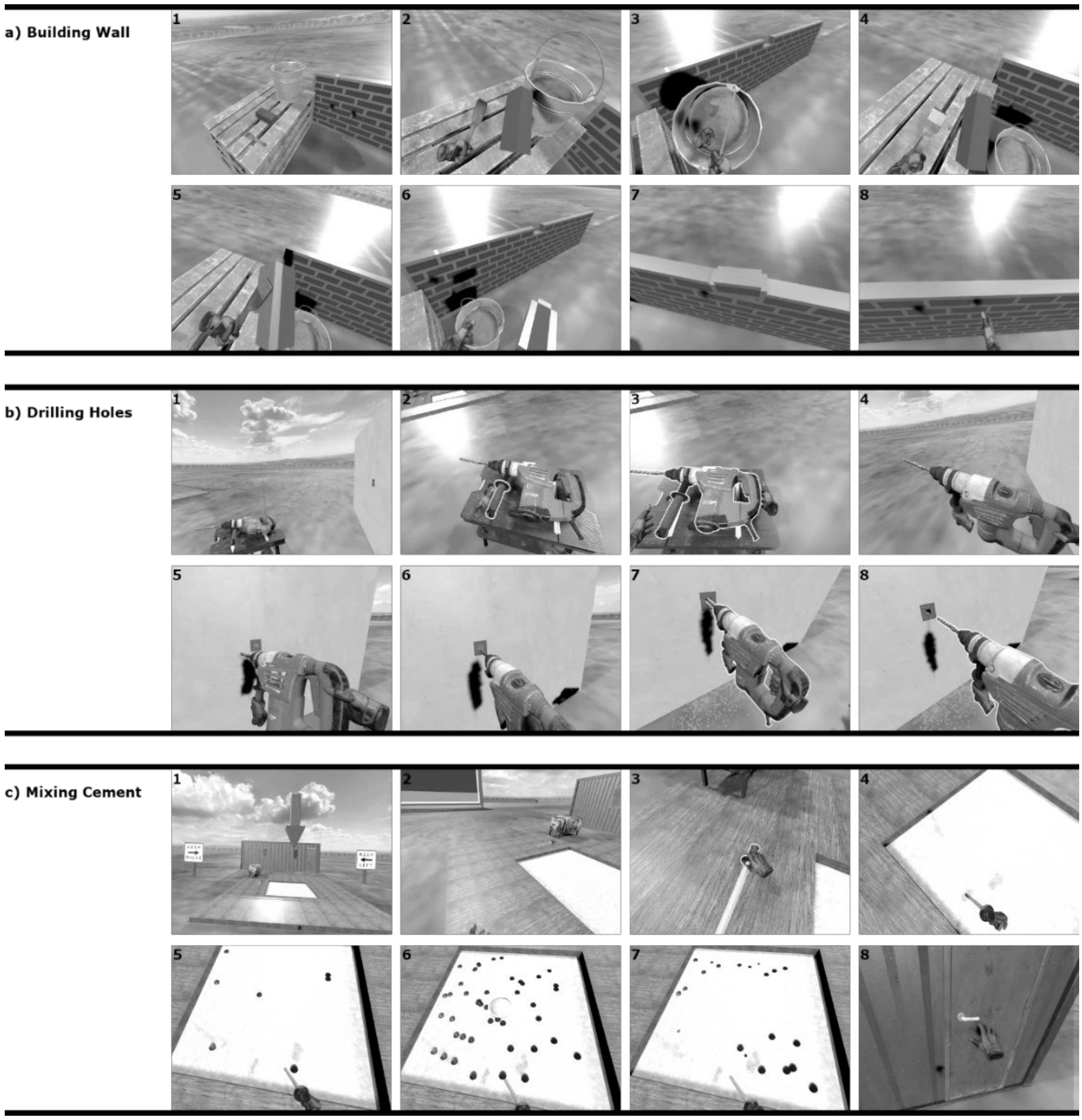

Figure 4.11: Screenshots of the tutorial tasks.

4.3.2.2 Participants

Before the actual study, a prior test of the whole system was done with a VR expert to uncover bugs or any other inconsistencies in the experience. For the main study, 16 participants[16] took part with a mean age of 30.06 (SD = 13.33). Fifteen participants identified as male, and one as female. Three participants were left-handed, and the other twelve were right-handed. Ten participants stated that they had no prior experience with VR, whereas three stated they had some experience (used < 10 times), and three were very experienced in using VR.

[16] An a priori computation for the required sample size was done in G*Power for repeated measures ANOVA ($\alpha = 0.05$, $1\text{-}\beta = 0.8$) with two groups and four measurements. It revealed a total sample size of 12 for large effect sizes ($f = .4$).

4.3.2.3 Safety and Ethics

Participants voluntarily participated in the study and gave consent for the use of their data. Before the study began, the process was explained to each participant, and they had a chance to ask questions at any time. Participants were informed that they could interrupt their participation and withdraw their informed consent at any time.

This study took place in February 2021, during the COVID-19 pandemic. The study was conducted according to the guidelines of the state of North Rhine-Westphalia that were in effect at the time. For additional safety measures, prior to each participant's arrival, the headset was sanitized with a disinfectant, and a new disposable hygiene cover was placed on the headset cover.

4.3.3 Results

First, RT data of the three conditions was compared and the accuracy was calculated to examine whether the signals were well perceived. Second, the scores of the Nasa-TLX questionnaire were determined and compared across conditions. Finally, the answers in the UEQ and SUS were computed. If not stated otherwise, as analysis tool *R* was used in version 4.1.2.

4.3.3.1 Reaction Time Analysis

Participants received eight vibration cues during each scene (two for each direction). Thus, 64 RTs were generated for each participant, and for each condition, the data set included 32 RTs (2 conditions x 4 scenes x 8 cues). In total, for 16 participants, the data set included 1024 RTs. This data set was filtered for timeouts, removing data rows of given cues on which a participant did not react, leaving a set of 958 RTs. Then, the data set was filtered by excluding RTs that were slower than two standard deviations above the mean of the remaining RTs for each condition and RTs that were faster than 200ms. The resulting data set contained 903 RTs, as shown in Table 15, with the RT count per scene, the means, and standard deviations. This overview shows that the lowest RT count is found for *Controller+Bricks* (105 RTs) and *Walking+Bricks* (104 RTs).

Table 15: Reaction Time (RT) means in milliseconds (ms) per condition and scene

Condition	Scene	RT Count	Mean	Std. Dev.
Controller	Baseline	121	560.17	152.80
	Bricks	105	875.13	301.54
	Drill	111	803.20	223.24
	Cement	111	656.77	203.55
	All	448	718.14	255.26
Walking	Baseline	123	536.92	153.20
	Bricks	104	768.38	252.52
	Drill	115	764.89	241.18
	Cement	113	637.35	209.77
	All	455	672.38	236.20
All		903	695.08	246.77

A boxplot visualization of the data shows that the RTs in the *Walking* condition were shorter on average than those RTs in the *Controller* condition for all four tasks Figure 4.12. The RT measures in the baseline measurement were fastest on average, followed by the task *Cement* and *Drill*. The slowest RTs, on average, are found in the task *Bricks*. However, when considering the used locomotion technique, the mean for *Drill+Controller* is higher than for *Bricks+Walking*.

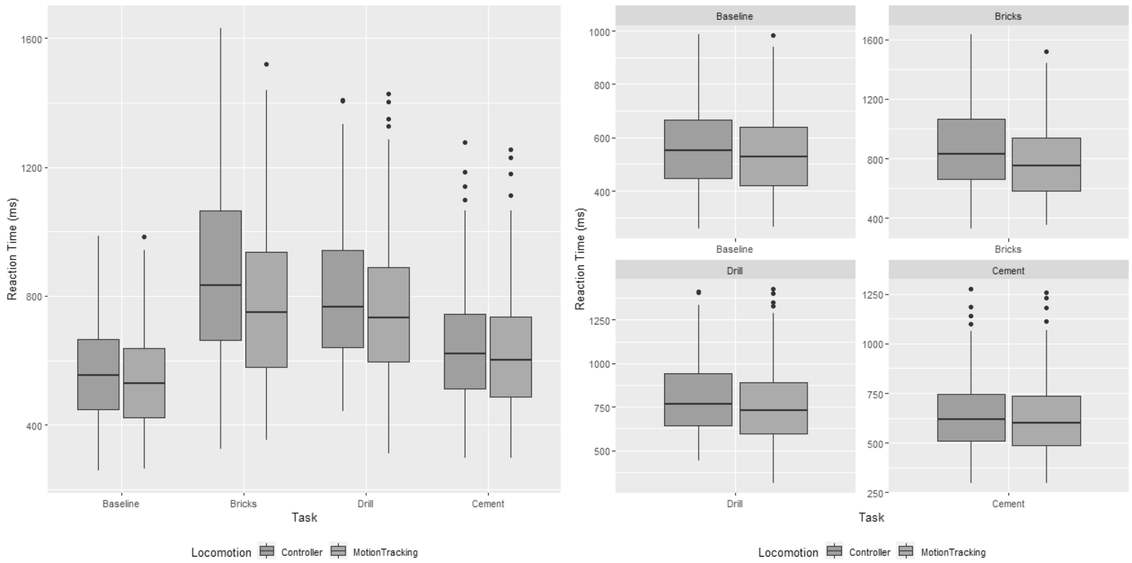

Figure 4.12: Boxplot diagrams of RT data.

Note. The left plot shows all tasks and locomotion grouped by task; the right plot shows side by side comparison for RTs in each task.

Kernel density plots revealed a wider spread of RT distributions for the three tasks (Figure 4.13). The upper plot shows the distribution of RTs among all tasks per condition. The lowest peak is found for the task Bricks, followed by Drill, Cement, and Baseline, supporting the order of means from the boxplot that Figure 4.12 suggested.

To investigate the effect of locomotion and interaction technique on the RT data, a two-way repeated measures ANOVA was computed in SPSS 28 with two levels of locomotion (walking, controller) and four levels of tasks (baseline, bricks, drill, cement). First, the means for each participant per condition and task were computed, leaving 128 data rows (= 16 participants * 4 tasks * 2 locomotion conditions). An analysis for outliers has identified six values as outliers, which were replaced by the respective mean values per Locomotion*Task. A Shapiro-Wilk test and QQ-Plots for each Group*Task were computed, showing that normal distribution can be assumed.

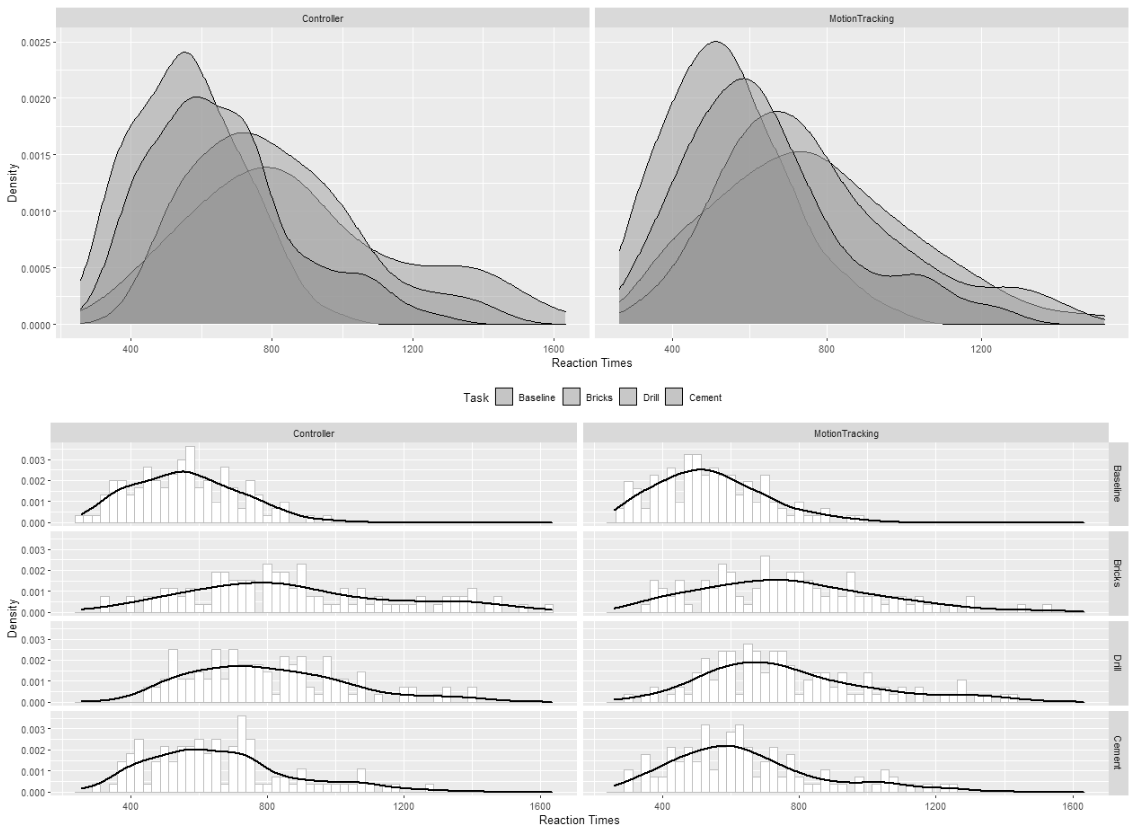

Figure 4.13: Kernel density plots for the reaction time data after data sanitization

A Mauchly's test indicated that the assumption of sphericity was not met for the factor *task* (p = .046). Therefore, a Greenhouse-Geisser correction method has been applied to adjust the sphericity of the data. The two-way repeated measures ANOVA revealed that there was a significant main effect of the used locomotion technique on participants' reaction times, $F(1,15) = 18.19$, $p < .001$, $\eta^2 = .548$. Participants showed faster reaction times when using (real) walking in VR ($M = 674.99$) compared to controller-based locomotion ($M = 736.45$).

Regarding the different tasks in VR, the ANOVA revealed that there was also a significant main effect of the task on participants' reaction times, $F(2.074,13) = 36.66$, $p < .001$, $\eta^2 = .71$. However, there was no significant interaction effect between the type of Locomotion and Task on participant's reaction time, $F(3,13) = 2.66$, $p = .092$, $\eta^2 = .381$.

Post hoc pairwise comparisons using the Bonferroni correction showed that the mean reaction time in the *Baseline* measure ($M = 547.62$) was significantly lower than in the tasks *Bricks* ($M = 849.59$), $p < .001$, *Drill* ($M = 787.02$), $p < .001$, and *Cement* ($M = 638.64$), $p < .001$. There was also a statistically significant difference in the task *Cement* compared to *Bricks* ($M_{Diff} = 210.96$), $p < .001$, and compared to *Drill* ($M_{Diff} = 148.39$), $p = .002$. The mean reaction times did not differ significantly between the tasks *Bricks* and *Drill*.

The study design used counterbalancing between the locomotion conditions to reduce the impact of practice effects. However, as a final step, the data was analyzed for practice/training effects on the dual task (RT task) between the first and the second session run (independent from the used locomotion technique). Means were computed for each participant for both test runs, resulting in a data set with 32 rows (16 participants x 2 session runs). After testing for normality with a Shapiro-Wilk test, a paired sample t-test was computed to investigate whether the means between both session runs differed significantly. According to the paired sample t-test, the average RT time in the second run ($M = 655.39$, $SD = 94.72$) was significantly lower than in the first test run ($M = 722.32$, $SD = 105.62$), suggesting that some practice effect on the dual task might have taken place, $t(15) = 3.9751$, $p < .001$; $d = 0.99$.

4.3.3.2 Accuracy and Error Rates

The accuracy with which the signals were responded to was calculated using *all* RT data and calculating the rate of timeouts to the vibration signals. The timeout value was defined as a maximum of 2 seconds for participants to react to the vibrations. Results for the accuracy are shown in Table 16 for the cues in each condition, split by task. The data reveals that the accuracy was comparable between the conditions. However, when also considering the task, participants made the most errors in *Walking+Bricks*, with an accuracy of 81.25, followed by *Controller+Bricks*, with an accuracy of 82.03 on average.

Table 16: Accuracy in percentage of detecting signals per condition and task

Condition	Scene/Task	Accuracy (Raw RTs, %)	Accuracy (Cleaned Data, %)
Controller	Baseline	98.44	94.53
	Bricks	89.06	82.03
	Drill	92.97	86.72
	Cement	92.19	86.72
	All	93.17	87.50
Walking	Baseline	99.22	96.09
	Bricks	86.72	81.25
	Drill	95.31	88.28
	Cement	94.53	89.84
	All	93.95	88.87

4.3.3.3 Workload and Task Difficulty

For each condition, participants filled out the Nasa-TLX. Figure 4.14 shows the means for each scale, grouped by locomotion. The ordinal scale allows ratings from 0-100, with higher values meaning higher load, except for the scale *Performance*, in which higher values translate to subjectively rated poorer performance.

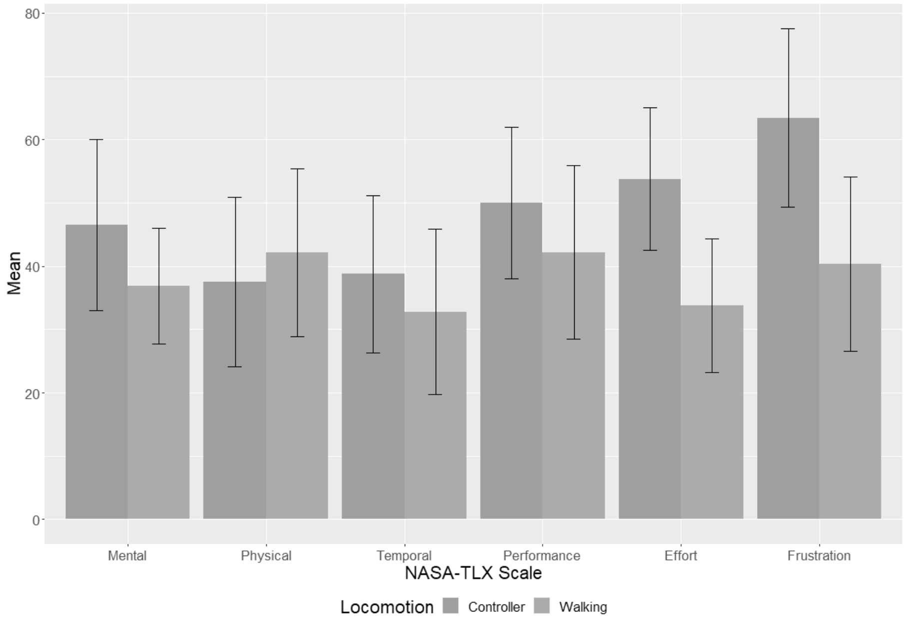

Figure 4.14: Barplot with Nasa-TLX means

The plot shows higher means for mental demand, temporal demand, performance, effort and frustration when participants were using the controller during the tasks (precise values in Table 17). Only the physical demand was rated higher for the walking condition. The largest difference between Controller and Walking conditions was found between frustration, effort, followed by mental demand, which were all rated higher for the controller condition.

Table 17: Results for the Nasa-TLX

Scale	Controller		Walking		Friedman Test
	Mean	**Std. Dev.**	**Mean**	**Std. Dev**	***p***
Mental Demand	**46.56**	27.61	36.88	18.61	ns
Physical Demand	37.50	27.26	**42.19**	27.02	ns
Temporal Demand	**38.75**	25.27	32.81	26.64	ns
Performance	**50.00**	24.49	42.19	28.05	ns
Effort	**53.75**	22.99	33.75	21.49	.008
Frustration	**63.44**	28.74	40.31	28.13	.005
Overall Workload	**48.33**	**26.06**	**38.02**	**24.99**	**ns**

Note. Sig. = significance, ns = not signicifant.

These results suggest that participants found the controller condition mentally more demanding. A Friedman test on the mental workload showed no statistically significant differences between both conditions, $X^2(1) = 3.77$, $p = .052$. Results for the physical demand, $X^2(1) = .29$, $p = .059$, temporal demand, $X^2(1) = 1.67$, $p = .197$, and performance, $X^2(1) = .07$, $p = .80$, did not reach statistically significant differences. Differences between the subjectively perceived effort reached statistically significant difference, $X^2(1) = 7.14$, $p = .008$, and between the frustration, $X^2(1) = 8.07$, $p = .005$. The overall workload did not show statistically significant differences between the ratings for Controller or Walking, $X^2(1) = 2.25$, $p = .134$.

4.3.3.4 Usability and User Experience

The UEQ was used to assess the user experience for both locomotion techniques. Its items are scaled from -3 to +3 (most negative to most positive), comprising 26 items with six scales: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty (Table 18). The SUS was used to assess the perceived usability. It consists of 10 items asking participants their opinion about the used system on a five-level Likert scale ("strongly disagree" to "strongly agree"). The mean results for both questionnaires are shown in Figure 4.15.

The system's usability was rated higher for real walking in VR ($M = 85.3$, $SD = 10.4$) than for controllers ($M = 75.9$, $SD = 19.2$). Both conditions were rated to have acceptable usability. Participants rated real walking in VR as 'excellent' and using controllers as 'good' (using the adjective ratings suggested by Bangor et al., 2009).

Table 18: Mean ratings for the UEQ

	Controller		**Walking**	
Scale	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev**
Attractiveness	1.69	0.91	1.90	0.71
Perspicuity	1.66	1.13	2.19	0.48
Efficiency	1.09	1.19	1.63	0.53
Dependability	1.59	1.03	1.53	1.01
Stimulation	1.47	0.90	1.63	0.63
Novelty	1.13	1.11	1.22	1.05

Regarding the user experience (UX), both locomotion conditions have resulted in a positive felt UX. The UEQ ratings revealed that the attractiveness (overall impression) of the system was rated better when using walking ($M = 1.90$, SD = 0.71) than for controllers ($M = 1.69$, $SD = 0.91$). Additionally, participants felt it easier to learn how to use the system (perspicuity) when using walking compared to using controllers. Also, they rated it more efficient to solve their tasks when using real walking. Regarding the hedonic quality of the system, participants rated the VR experience as more stimulating and interesting (novelty scale) when using real walking. Only on the scale dependability, participants rated the controller-based version ($M = 1.59$) slightly higher (walking: $M = 1.53$).

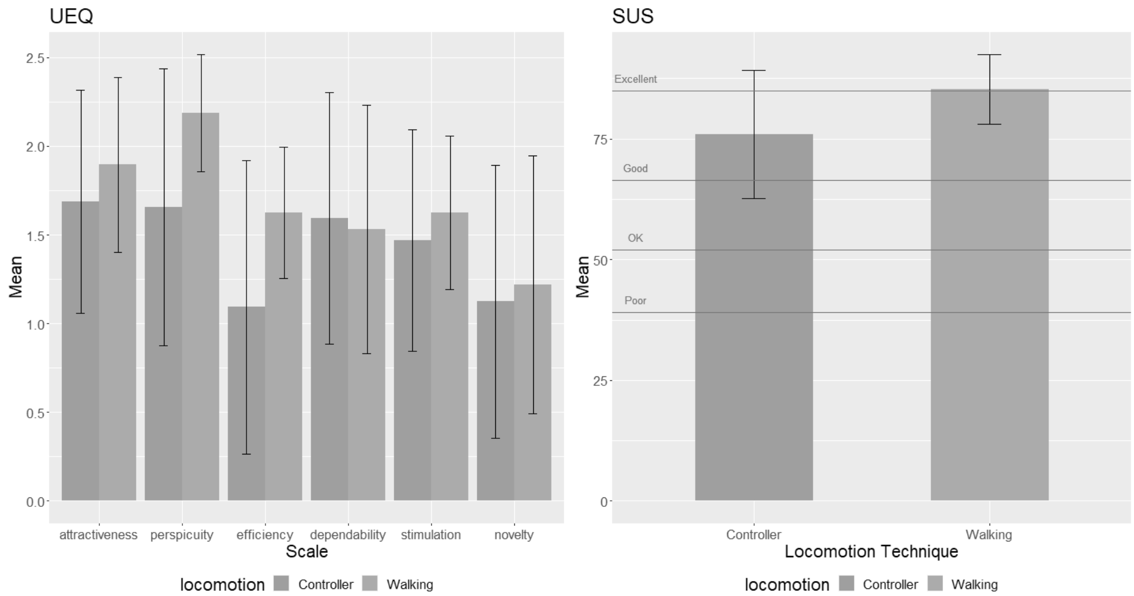

Figure 4.15: Ratings of the User Experience Questionnaire and System Usability Scale

4.3.3.5 Additional Comments

After finishing the two test runs, the participants were asked about certain aspects that had caught the attention of the test administrator during their participation (due to the long duration of the individual sessions, no extensive interviews were conducted). Regarding the different tasks, participants mentioned two strategies for the task 'Bricks', although only one was presented in the tutorial scene. Most participants started by applying mortar to the brick and putting it into the wall (as shown in the tutorial). In contrast, the majority changed the strategy by first applying mortar on one side of the brick, putting the brick in the appropriate place in the wall, and then coating the other side with mortar. For the task 'Drill', it could be observed that some participants did not successfully pull the hammer drill out of the wall after drilling. This observation was due to minor bugs in the implementation, as the hammer drill sometimes lost the connection to the controllers depending on hand movements.

Finally, participants reported that they prefer real walking over controller-based locomotion for complex tasks requiring precise interaction. In the controller-based locomotion, participants stated they were sometimes overwhelmed. For example, the drilling hammer sometimes dropped because participants had to use the controller to hold and start the hammer drill and simultaneously respond to the vibration stimuli.

4.3.4 Discussion

To summarize, the used locomotion technique and the task complexity affected the participants' mean RT. The results showed that the combination of interaction complexity of the task and choice of VR locomotion impact mental demand and overall workload, although both concepts did not reach statistically significant differences on self-reported measures (TLX-scores). It was shown participants had longer RTs when using controller-based VR compared to real walking in VR, indicating that cognitive effort in the walking condition was lower than in the controller condition. As task complexity decreased, so did RTs (Figure 4.12), and the accuracy of RTs increased (Table 16).

However, when considering both locomotion and task, the results have shown that controller-based locomotion on a task with medium interaction complexity ('drill') can lead to higher RTs on average than real walking on a task with a high interaction complexity ('bricks'). An explanation for this result could be derived from Wicken's MRT (see Section 2.1.3.3), as the controller-based locomotion technique competes for the same attentional resources as the secondary task (to react on vibrations).

The self-reported TLX scores indicated that controller locomotion was more frustrating, needed higher effort, higher temporal demand, and mental demand, and resulted in a poorer performance than real walking in VR. However, only frustration and effort did reach statistically significant differences between conditions. The UX-ratings support the overall notion that real walking was preferred by participants. One effect that could have led to these results was that controller-based VR was rated to have worse usability than real walking VR, as indicated by the SUS scores.

The literature shows different findings in this regard. On the one hand, locomotion techniques with a less natural interface seem to increase spatial working demands (Marsh et al., 2013). On the other hand, a study comparing a gamepad controller and real walking in VR did not find significant differences between task performance and completion (Nabiyouni et al., 2015). However, no other literature was found that explicitly compared the impact of controller-based locomotion and real walking on cognitive effort. Thus, further research is needed on this topic to generalize results.

Finally, to discuss the results based on the use case of a VR Lab for testing vibrotactile warnings for occupational safety, the results indicate that controller-based control can be used for such evaluation purposes. When exploring time-critical responses to the emergence of hazards, controller-based control appears to produce a longer response time overall than real walking, as the locomotion technique competes for the same mental resources as the reaction task. If RTs to vibrotactile warnings in (controller-based) VR simulations are shorter than a pre-defined time threshold, the reaction time should be even shorter with real walking. Even though this generalization is highly context-dependent and needs to be validated with real-world field tests due to other environmental factors, the result is still preferable to the case that controller-based control could have led to shorter RTs.

4.3.5 Limitations

Due to the study's design, only two locomotion techniques were compared. Thus, it remains unclear how other locomotion techniques would compare to the ones used in this study, such as walking-in-place or the use of treadmills.

Then, the validity of the results is limited by the fact that no construction workers participated in the study, and the activities in the VR scenes were only performed by nonprofessionals. However, the focus of the study was not to test how well the virtual tasks were perceived but to investigate the influence of two locomotion techniques on the cognitive effort of the VR experience.

Finally, the study lacks detailed post-VR experience interviews to evaluate the general system, which could not be conducted due to the long duration of a single study session. Here, statements of the participants were included sporadically, observations were noted, and in case of doubt, specific observations were asked by the study facilitator.

4.4 Summary

Finally, this summarizing section evaluates the results and observations for both studies. The first study investigated the detection rate and RTs to vibrotactile cues with and without physical movement in VR and reality. The study has shown that the vibrations were perceived similarly for both conditions of physical activity and that VR is sufficient to produce reaction delays and errors similar to those that occur in reality. Participants felt an increased presence due to the real walking in VR. However, the interaction space was limited by the lighthouse system of the VR hardware and the size of the room. These boundaries also minimized the interaction space of the VE.

The second study compared RT data between two locomotion techniques in VR: real walking and controller-based locomotion during three tasks with different interaction complexity. The analysis has shown a higher cognitive demand for controller movements compared to real walking, which was also indicated by the subjective scores on workload and mental demand in the Nasa-TLX. While participants only used the controllers to interact with objects and to react to the RT task during real walking, in the controller condition, they had to additionally use the controllers for their movements inside the scene. This overload of controller functions may have complicated the interaction to react to the vibrotactile stimuli. Thus, controller-based locomotion in VR Labs is a suitable technique as it allows the exploration of larger VR scenes and even increased cognitive load of participants compared to real walking due to the controller interaction.

It should be noted, that the results of the two studies in Section 4.2 and 4.3 are only comparable with each other to a very limited extent since a different technical setup for RT measurement was used. While in the first study, a smartphone application was used for the communication with the vibrotactile belt, in the second study, the communication was done via the VR hardware.

As a final remark, the vibrotactile feedback in both presented studies had no other meaning than to serve as an indicator of cognitive performance as participants had to react to vibrotactile cues. Thus, it remains unclear if (directional) vibrotactile feedback can be applied as hazard warning signals. Therefore, vibrotactile warnings will be examined and discussed in the following study presented in Chapter 5.

5 Vibrotactile Proximity Warnings and Behavior Adaptation

Based on the assumptions and previous literature described in Sections 2.2.5 (Vibrotactile applications) and 3.1.4 (Proximity warning systems), vibrotactile wearables have the potential to alert and warn workers in time in case of proximity hazards. However, it is hardly possible or justifiable to evaluate such wearable prototypes in real environments with potentially dangerous situations. Consequently, the evaluation of such systems (Section 3.1.4) is mainly limited to technical evaluations in which participants can concentrate solely on the detection of vibrotactile cues (i.e., Cho & Park, 2018, p. 14) or 'artificial' task experiments by inhibiting visual and auditory senses of participants to solely react to vibrotactile cues (i.e., J. Park & Sakhakarmi, 2019, p. 9). Thus, in this study, it is explored how VR simulations can be used for the evaluation of such prototypes. It examines which effects directional vibrotactile warnings have for recognizing hazards and how the warnings affect the behavior in VR.

5.1 Research Objectives

The study aims to explore the effect directional vibrotactile warnings have on hazard recognition in the context of a construction site setting under workload. The study analyzes whether and how vibrotactile warnings are perceived during a dual-task in VR. On real construction sites, workers are usually engaged in one or more tasks while permanently observing safety precautions and looking out for their safety. Therefore, a VR environment was created where participants faced several safety-critical situations while solving a pick-and-place task. The hazards were indicated via the vibrotactile warning system.

This study investigates the effect of directional vibrotactile warnings on recognizing hazards and near-miss accidents in a VR construction setting. For this study, a system was used that combines a VR environment and a vibrational wearable (the same as shown in Figure 4.8) that released vibration alerts in four directions, indicating a hazard in the direction of the vibration. This explorative study was done in a VR Lab at the Ruhr University Bochum between March and April 2021. As the COVID-19 pandemic was still ongoing, additional safety aspects had to be considered during this study (see Section 5.8).

5.2 Study Design

This study used a within-subjects design. Three VR scenes were implemented to investigate how hazard recognition is influenced via directional vibrotactile warnings. Whereas in Chapter 4, the vibrations were used to gather data on reaction times toward the vibration cues, here, several parameters are used to configure the vibration cues in order to investigate their relevance for warning purposes: the vibration intensity, repetition of vibration pulses, pause between vibration pulses, and the duration of vibrations. In addition, the influence of the virtual environment's visual design on the participants was evaluated: Two VR scenes were identical in their content but differed in their visual fidelity.

The independent variables included the visual fidelity of VR scenes, the intensity and duration of the vibrations, and the hazard recognition in the VE. Implicitly, the direction of warnings was also an independent variable. However, the warning directions varied based on the situation and movements of participants in the VE. As dependent variables, two parameters are used to understand the workload of participants: the data of reaction times (RT) to the vibration cues and the results of the (raw) Nasa-TLX. In addition to the RTs, the study collected data concerning the number of hazards participants recognized. To analyze the effect of the different visual fidelities on presence, the iPQ is used.

The Sickness Simulator Questionnaire (SSQ) was completed before and after VR exposure to detect any motion sickness symptoms that might have occurred. Using the SSQ allowed to understand if there might be an impact of motion sickness symptoms on the performance of the participants. The SUS was used to ensure that the system offers sufficiently good usability. In addition, questions about usability are also asked in the semi-structured interviews (Appendix J).

5.3 Virtual Environment and Hazards

This study used a VR simulation of a construction site with multiple hazards that participants could face during the experience. The model was inspired by the observations made in the field and by other examples of construction sites in Germany. For the VE, insights from the site safety inspections (see Section 3.1.1) were integrated to include realistic hazards and to create a visually and auditorily realistic character. As VR hardware, the HTC Vive Pro was used.

5.3.1 Overview of the Virtual Environment

The virtual construction site was modeled in such a way that the site included a building shell, an excavation pit, demolition work, a parking lot, and stockpiled material. A top-down view of the construction site is visualized in Figure 5.1. Overall, the aim was to create a realistic and plausible appearance of the construction site, which was the reason for modeling the construction site in the middle of an urban landscape and placing it between two busy streets. Traffic was added to the streets, a natural sky was used, and objects like trees, houses, and skyscrapers were added, to increase the authenticity of the environment.

Figure 5.1: Top-Down view of the virtual construction site.

Several construction vehicles were placed on the extensive terrain of the construction site. Three moving construction vehicles were added, which repeatedly drove over the site to increase the dynamic of the virtual construction site: a lorry, a compactor, and an excavator (Figure 5.2). In addition to the moving vehicles, multiple static and parked vehicles were added. Then, many virtual objects were placed into the seen to increase the "visual noise".

Figure 5.2: 3D models of used vehicles: lorry, compactor, and excavator.

For further dynamics, construction workers were added. Some of these workers were static, others walked around the construction site or were performing tasks. For the soundscape of the construction site, a freely available recording of a construction site was also used to give the VE a visual and auditory reminiscent of a real construction site. A typical sound image of a construction site can be heard in this audio recording. Additional sound loops of a moving construction vehicle, an angle grinder, and a jackhammer were used to ensure a matching soundscape to the visual depiction of the scene. The visual sequences in the scene were mapped according to the audio loops[17] to avoid a noticeable mismatch between the audio and visual presentation. Sound sources were applied with the *unity* component of 3D sound[18], to enable spatial sound effects, i.e., vehicle sounds became louder when approaching and the direction of sound sources could be noticed.

Figure 5.3: Bird's eye view on the construction setting

5.3.2 Scenes and Task

Three scenes were designed for the virtual construction site, where users had to pick up several objects and bring them to a specified place. Based on the experiences in the two studies presented in Sections 4.2 and 4.3, the requirements for the task were that it should require participants to focus on something other than the reaction to vibrotactile warnings and that it should not require too complex interactions but be reasonably realistic for the construction setting (see also the requirements in Section 3.3.7). This 'pick-and-place' task was used to walk longer distances over the VE, which guaranteed that participants would face multiple hazards during the VR experience. In addition to the three scenes on the site, a tutorial scene and a scene for the reaction time baseline testing were modeled.

As locomotion technique, controller-based locomotion was used as it allowed the use of an open space scenario and to confront participants with multiple and different hazard spots. In all scenes, the digital representation of the participants was wearing a

[17] The sounds used were:

Angle Grinder https://freesound.org/people/domiscz/sounds/461728/

Jackhammer https://freesound.org/people/Garuda1982/sounds/427757/

Driving Vehicle https://freesound.org/people/Yuval/sounds/209992/

[18] https://web.archive.org/web/20231014064403/https://docs.unity3d.com/Manual/class-AudioSource.html

construction helmet, which could be seen in the top area of the field of view, as shown in the screenshot in Figure 5.4. For images in the following sections of this section, the helmet was removed for the screenshots.

Figure 5.4: Participants' view showing parts of the helmet in the upper field-of-view.

5.3.2.1 Tutorial and Baseline Scene

An additional tutorial scene was modeled to familiarize participants with the VR hardware and the interaction technique. The scene contained a room where multiple objects were lying on a table that could be grabbed (see Figure 5.5a). The participants had no task inside the tutorial room but were asked to move around and try to grab objects.

For the reaction time baseline testing, a neutral room was used so that participants could fully concentrate on the RT task. The room had no objects besides a menu, which was placed inside the room with one button to give participants the control to start the baseline testing on their own whenever they were ready. The baseline test was designed to get participants' RTs without any disturbances and when they could focus entirely on the vibrotactile signals. During the baseline test, 50 vibrotactile signals with different vibration intensities and patterns were applied.

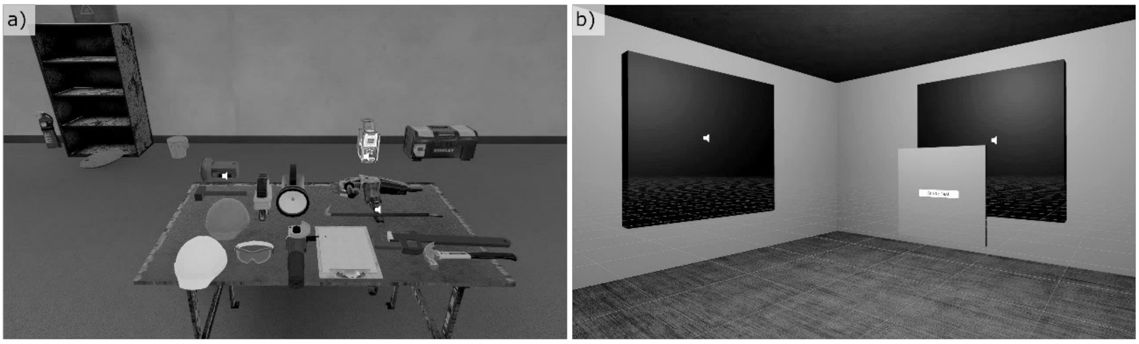

Figure 5.5: VR tutorial scene (a) and scene for baseline test (b).

5.3.2.2 Scene 1a: Hazards on the Ground of the Site

The first scene was based on the ground of the construction site (see Figure 5.6a). In the following sections, this scene will be therefore referenced as *Ground*. As task in the scene, participants have to collect a total of 7 garbage bags. The bags were distributed around the site and had to be brought to the garbage container. During the task, the participants had to pass multiple hazards and could take up two bags at the same time. Five different hazard types were used:

- Moving vehicles
- Overhanging material
- Being under a crane load
- Walking through a work area of others
- Contact with electrical power.

Figure 5.6: Starting view of the scene 'Ground'

5.3.2.3 Scene 1b: Hazards on the Ground of the Site (Low Fidelity Version)

The same scene was chosen again in a more abstract form to evaluate whether the visualization impacted the performance and the experience of the participants. This scene will be referenced as *Ground-LoFi* in the upcoming sections.

The task, the dynamics, and the number of hazards in this scene were the same as in *Ground*. While some objects were the same as in *Ground*, many surrounding objects were removed or simplified. For example, simpler or abstract models were used, i.e., of the lorry, and simpler textures were added (see Figure 5.6b). By reducing the number of objects in the scene and using simpler textures, the scene should make it easier to attend to moving objects or hazards. All particle effects were removed to minimize the visual disturbances, i.e., the smoke the lorry produced.

5.3.2.4 Scene 2: Hazards on the Roof of the Construction Shell

The second scene took place on the roof of the construction shell (see Figure 5.7) in the same construction environment and will be referenced as *Tools* in the following sections. Using the same environment, animations and other dynamics of the surroundings were also present in this scene. For example, moving construction vehicles or road traffic were visible from the roof. The task for this scene was to collect several tools that were placed around the site. Nine tools had to be collected. Six different hazards can occur when working on the task:

- Defective fall protection
- Missing fall protection
- Falling material
- Overhanging material
- Being under a crane load
- Walking through a work area (angle grinder).

Figure 5.7: Starting view of the second scene 'Tools'

5.3.3 Hazard Types

This section gives an overview and visual examples of the used hazards in the VE. In the scenes, several static and mobile hazards were integrated.

5.3.3.1 Hazard: Moving Vehicles

Based on the data provided by the DGUV, in 2020, 16.782 accidents were categorized as "being hit/colliding with a moving object", which account for 14.3% of all reported accidents (DGUV, 2021). To adequately reflect this type of accident in the VE, in the scene *Ground*, moving vehicles and crane loads were added to the VR scene. Three different construction vehicles were integrated, which repeatedly drove along predefined paths on the construction site at different times: a lorry, a compactor, and an excavator. The vehicles had colliders attached which allowed event logging when a participant was inside that radius. Using this approach, a single detection zone with a radius of 7 meters was simulated around the vehicles (see visualization in Figure 5.8).

Figure 5.8: Single detection zone around a vehicle

Note: The visualization of the red area beneath the lorry was not visible during the VR experience and is only displayed in the screenshot.

Using predefined paths along the construction site ensured that the vehicles repeatedly crossed the path to be taken by participants and thus became potential hazards. To keep the warnings simple, the warning area around the lorry had only a single warning zone (detection zone). As soon as a participant was inside the detection zone of the vehicle, a warning message was sent to the vibrotactile belt.

5.3.3.2 Hazard: Falling Objects

As described in Section 3.1.1, there is a risk of being injured by objects falling from a height on construction sites. Typically, objects can fall off crane loads when the load is poorly secured. This is implemented in all scenes, as shown in Figure 5.9, a) for the scene *Ground*, b) accordingly for the *Ground-LoFi* scene, and e) for the scene *Tools*. During the runtime of the scenes, the crane moves sideways back and forth, and the crane load moves forward and backward. Thus, the danger zone moves along the user's walking paths. Even though no objects fall from the carried container in the VE, users get a warning as soon as they stand directly under the crane.

Figure 5.9 also displays multiple hazards of material that protrudes over the edges. In c) and d), a plank and a steel beam are above the red bag, and a chainsaw is above the black bag. In f), many wood planks are standing over the plateau's edge. When participants passed the position where the screenshot was taken, a small metal pipe started rolling beside the wood planks and fell.

Figure 5.9: Implemented hazards of falling or potentially falling objects

5.3.3.3 Hazard: Clear Workspace

Work areas of several other trades should not be too close to each other to prevent the trades from endangering each other with their work activities. For instance, to avoid other workers getting injured by flying parts or others. Thus, workers should avoid walking through each other's work areas.

Two hazard spots were added to the scene *Ground* to represent this scenario. A worker with a jackhammer was added at the edge of the walkway. The jackhammer used sound and was animated with an up-and-down movement. Additionally, sand dust and larger particles were visualized (Figure 5.10). Additionally, in another area, a worker used a drilling hammer during demolition work (Figure 5.9c and Figure 5.9d). This spot was animated with occasional falling bricks.

Figure 5.10: Construction worker using a jackhammer

For the scene *Tools*, a hazard spot was located on the highest level of the shell construction site. Two construction workers were placed on an elevated level, working with an angle grinder. A recurring spark spray was added to visualize the work (see Figure 5.11). In addition, a suitable audio recording of angle grinder cutting was integrated into the scene.

Figure 5.11: Hazard area, two workers with an angle grinder

5.3.3.4 Hazard: Falling from Heights

Accidents from height were integrated as another potential source of accidents, as around 43% of all deadly accidents were based on falling from heights (DGUV, 2021, p. 90). For this purpose, five locations with missing or defective guardrails were inserted in the scene *Tools*.

Figure 5.12: Overview of the scene 'Tools' with missing and defective fall protection

5.3.3.5 Hazard: Contact with Electrical Power

For this category of potential hazards, a malfunctioning generator was placed on the site for participants to walk past. The generator used irregularly sprayed sparks and emitted corresponding electrical noises. Even though this visualization may not be close to reality, the sparks indicated the threat of electric shocks.

Figure 5.13: Malfunctioning generator spraying electrical sparks

5.3.3.6 Additional Moving Objects

Besides the dynamic objects on the construction site, two types of animated objects were added to the VE, as well as an object reducing the visual field of participants:

1) two airplanes repeatedly flew over the VE at some distance,
2) to the left and right of the construction site, two roads with traffic are placed, and
3) participants were fitted with a helmet, which resulted in a white/gray area in the upper field of vision.

Placing these details into the VE was to investigate if participants would notice them. Whether participants would notice these objects also provides insight into the effort developers or researchers must expend in modeling a dynamic VE for such evaluations.

Figure 5.14: Two airplanes (red circles) were flying repeatedly over the construction site

5.4 Vibration Belt and Parameters

For this study, the same vibrotactile belt was used, which is described in Section 4.3.1.2. The overall system was adapted to the needs of this study design as no RT task was used as a secondary, parallel running task. However, the vibration signals were used as warning messages and thus only displayed when a hazard in the VE occurred.

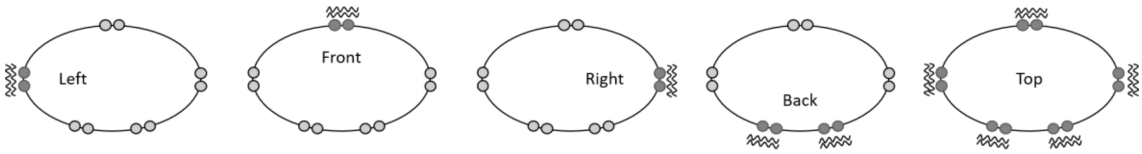

Figure 5.15: Used vibration directions

Five vibration directions were implemented: front, right, left, back, and above/top (see Figure 5.16). The direction indicating a hazard from above was mapped by using simultaneous vibrating of all four directions. A script was implemented, which allowed to configure each relevant vibration parameter from within the VE:

- the intensity (in percentage),
- the duration of a single vibration (in milliseconds),
- the repetition of a single vibration, and
- the pause between vibration pulses (in milliseconds).

Figure 5.16: Participant wearing the vibrotactile belt during a study session

The standard vibration cues with which each participant started used an intensity of 100%, were 200ms long with 100ms pause between vibration pulses and three repetitions of vibrations. This design was chosen to be perceived as 'urgent' (cf. Saket et al., 2013). However, while in *Ground* and *Ground-LoFi*, vibration cues were always applied with 100% intensity, during the VR scenes *Baseline* and *Tools*, the cues also randomly changed to other configurations, with three levels of intensity: *low* (50-65%), *medium* (70-85%), *high* (90-100%) to explore how well other intensities would be recognized. Coreless vibration motors were used (21.7 x 7mm, 7500RPM, 3V, see Figure 2.9, bottom-left) and the ESP32 microcontroller output pins operate at 3,3V (maximum).

Other factors were:

- Duration: 1000ms, 600ms, 500ms, 450ms, 200ms, 150ms, 100ms
- Pause between vibrations: 600ms, 500ms, 450ms, 200ms, 100ms, 50ms
- Repetition of vibrations: 4, 3, 2.

5.5 Measures

This exploratory study involved measuring and surveying several concepts related to VR experiences and their feasibility as an evaluation tool (an overview of measurements is given in Table 19). Besides general demographic data, prior experience with VR was asked of each participant, as prior experiences could influence their views on the prototype in this study. Before and after the VR parts of the study, participants filled out SSQ to compare whether motion sickness symptoms occurred (Kennedy et al., 1993).

With the Nasa-TLX, the overall subjectively experienced workload was measured. Its item mental effort was also used to gain insights about cognitive effort during the study. RT data is used to rate how fast participants reacted to a vibrotactile warning. The detection rate of vibrotactile cues was assessed by computing the error rate of missed reactions. A baseline measure was used where participants could fully concentrate on the task to compare their cognitive performance during the scenes.

After the baseline measure, participants filled out five items about how they perceived and interpreted the tactile signals (Tactile-Q, Appendix K). These exploratory items were developed to understand how participants would interpret vibrotactile cues on the body *before* they were given any meaning in the VR scenes 2-4.

Finally, semi-structured interviews were used to get an in-depth understanding of participants' views. During the interviews, participants were asked which hazards they noticed. They were shown an overview of the virtual environment for this question and reviewed all hazards with the study facilitator. After questioning the recognized hazards, the participants were also asked if they noticed the additional objects of interest: airplanes, streets, and the helmet.

Table 19: Overview of measurements

Measure / Concept	Tool / Method	When applied
VR Experience	- Demographics Questionnaire, - Interview	Demographics before VR experience, Interview, after VR experience
Motion Sickness Symptoms	- SSQ, - Interview	SSQ before and after VR experience (SSQ-Pre, SSQ-Post), Interview, after VR experience
Workload	Nasa-TLX	After each VR Scene (Baseline, Tools, Ground, Ground-LoFi)
Feeling of Presence	- iPQ, - Interview	iPQ after each VR Scene, Interview, after VR experience
Cognitive Effort	- RT, - Nasa-TLX Item	RT during VR Scenes
Vibrotactile Cue Detection Rate	RT (Error Rate)	RT during VR Scenes
Recognized Hazards	Interview	Interview, after VR experience
Interpreting Tactile Meaning	Tactile-Q	After Baseline-Test
Usability	- SUS, - Interview	After VR scenes
Surrounding dynamics	Interview	after VR experience
User Experience, Immersion	Interview	after VR experience

The iPQ was used to assess the feeling of presence after each VR scene (Appendix G). In the interviews, participants were asked about their subjective view of the environment, the audio, and the visual design to gain a more detailed view of their experienced presence in the scene.

The SUS was used to measure the system's usability to ensure that the results were not affected by a poor usability of the system. Finally, a semi-structured interview was conducted with each participant. The interview focused on general questions regarding the pre-knowledge of VR or the domain of construction sites, the usability and user experience of the used interaction methods, the task within the VE and the VE itself, the hazards, and the vibrotactile signals.

5.6 Procedure

The procedure of this study (Figure 5.17) is outlined as follows: After welcoming each participant, they were handed out the informed consent, a demographic questionnaire and were informed about the study procedure in general. The participants were also informed that they could experience symptoms of motion sickness and stop their participation at any time during the study.

They filled out the SSQ before starting any VR experience (referred to as ‘SSQ-PRE’ in the following sections). Then, the participants were put on the vibrotactile belt and checked if it fits properly and, if necessary, adjusted. After that, the participants were given the VR controllers and a brief explanation of how to use them, before putting on the VR headset. As VR system, the cable-based HTC Vive Pro was used with a disposable hygiene cover for each participant.

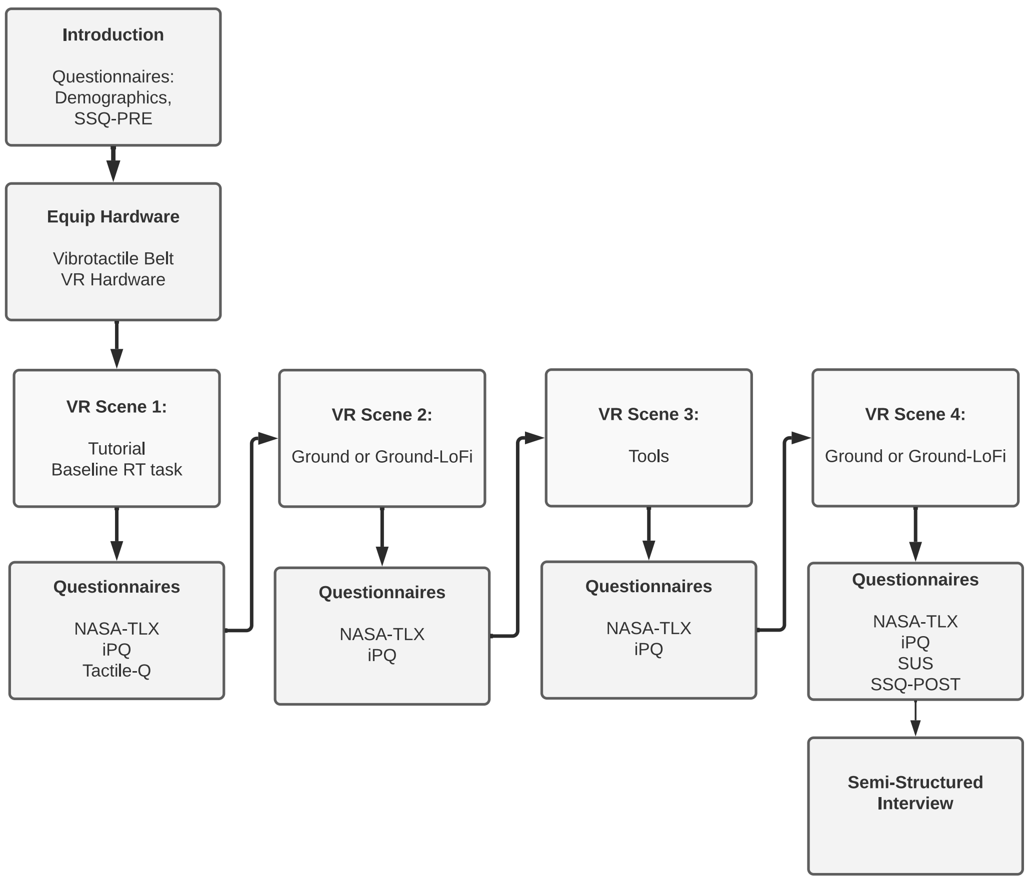

Figure 5.17: Process showing the study procedure

When participants felt ready, the tutorial VR scene was started, where the participants could try out the controls and grab objects. No time limit was applied to the tutorial scene, and participants were allowed to ask questions about the VR controls and environment.

Only when the participants gave the feedback that they were ready, they were teleported to the next scene, the 'baseline room'. Inside the baseline room, the participants did an RT task to get their RTs to vibrotactile cues when they could concentrate fully on the vibrational cues. After finishing the baseline test, participants put the HMD aside and filled out the (raw) Nasa-TLX, the iPQ, and a short questionnaire about vibrotactile cues (Tactile-Q).

In the second VR scene, participants started either with *Ground* or *Ground-LoFi* (Figure 5.18). Before they again put on the VR headset, they received the explanations needed to fulfill the task and the information that occurring vibrotactile cues were warning messages for hazards in the direction of the cue. They were asked to react as fast as possible to the vibrotactile warning with a specified controller button. When they had no further questions, the scene started. After finishing the task, the scenes stopped, and participants put the VR hardware aside to fill out the Nasa-TLX and the iPQ. This procedure was repeated in the next scene (*Tools*).

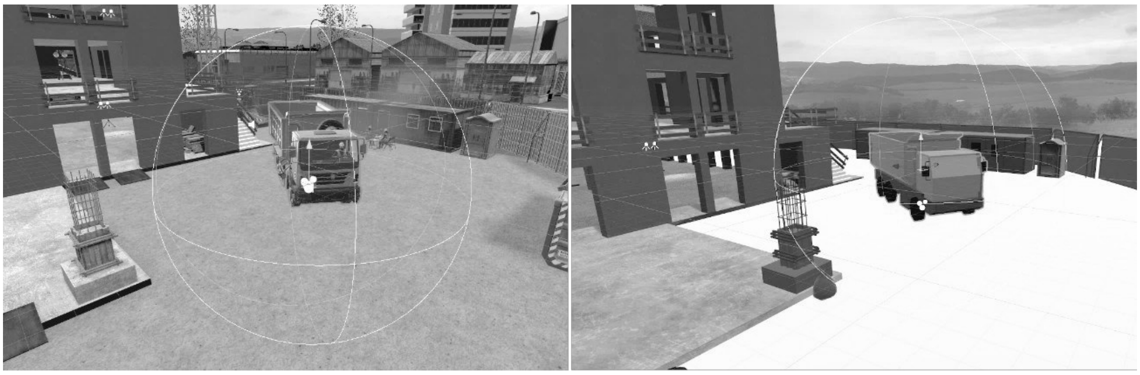

Figure 5.18: Comparison of the scenes Ground and Ground-LoFi

Finishing the last VR scene, participants were freed from the VR hardware and the vibrotactile belt. Then they filled out the Nasa-TLX, the iPQ, the SUS, and the SSQ. Finally, a semi-structured interview was conducted with questions about usability, user experience, overall VR experience, recognized hazards, and vibrations (guideline in Appendix J). One study session took between 1h – 1,5h.

5.7 Participants

Sixteen participants (5 female, 11 male) took part in this study. Fifteen participants had a computer science background, and one studied an interdisciplinary major (ethics, business, law, and politics). Fourteen participants were computer science undergraduates recruited from the course "Human-Computer Interaction" at the Ruhr University Bochum during the winter term 2020/2021. Participant's ages ranged from 20-27 years ($M = 22.63$, $SD = 2.12$).

For exploratory reasons, two of the sixteen participants did the study without the vibrotactile belt. Thus, their data was not included in the statistical calculations. However, their interviews were included in the analysis.

Regarding their prior experiences with VR, six participants stated they had no prior experience, eight participants were novice users but had at least tried VR once, and two were experts who owned VR HMDs and who had experience in developing for VR. Only four participants stated they had prior knowledge of construction site work.

5.8 Safety and Ethics

Participants were informed about the content of the study before participating. They were handed out the informed consent and had the chance to ask questions anytime. Participants were also informed that they could stop their participation at any time and encouraged to do so as soon as signs of motion sickness would appear.

At the time of the study, between March and April 2021, the COVID-19 pandemic was ongoing. The study was complied with all pandemic regulations in North Rhine-Westphalia in effect at the time. While conducting the study, only the participant and study facilitator were in the same room. In addition, both wore an FFP2 mask, and the windows were opened. To further minimize the risk of infection, there was, at minimum, a 15-minute break between the runs of two participants, allowing the room to be fully ventilated.

5.9 Results

If not stated otherwise, the quantitative analyses were computed with *R 4.1.2*. The semi-structured interviews were transcribed and then coded with *MaxQDA Analytics Pro 2020*. The qualitative results of the interview and the coding process are not described as standalone, but each of the following subsections is enriched with the statements of participants and general results gained from the interviews.

5.9.1 Reaction Times and Error Rates

For the comparison of RTs across all scenes, the data set was filtered for vibrotactile warnings with the highest intensity level, as these were applied in the scenes *Ground* and *Ground-LoFi*. In contrast, the scenes *Baseline* and *Tools* used also randomly changing intensities. The data set was then filtered for correct RTs, RTs slower than 200ms and faster than two times the standard deviation for each scene. Due to this data preparation, thirteen data sets were considered for this analysis. The data was first aggregated for each scene and warning direction to investigate how well the vibrotactile warnings have been detected. Descriptive statistics are listed in Table 20, showing the total counts, response accuracies, means, and standard deviations.

The data shows that the overall accuracy for all scenes is higher than 88%, whereas the highest accuracy and fastest RTs are achieved in the Baseline measure. Vibrotactile warnings applied to the back of the participants was the rarest warning direction (*Ground* = 9, *Tools* = 16, *Ground-LoFi* = 5), showing that hazards coming from behind occurred substantially less than others. From the observations during the study, it is also known that participants moved backward in VR only rarely, thus also reducing the chance of moving backward into a hazard. A visual inspection of QQ-Plots of the data set divided by scenes and directions did not reveal any peculiarities of the distributions of RT data by warning direction.

Table 20: Warnings across all scenes and cue directions (intensity level ‘high’)

Scene Warning Direction	**Total count**	**Accuracy**	**Count after data clean-up**	**Mean**	**Std. Dev.**
Baseline	**230**	**98.70**	**211**	**595.14**	**228.48**
Back	43	97.67	39	600.74	208.98
Front	42	100.00	39	587.90	206.73
Left	45	95.56	41	644.46	278.95
Right	46	100.00	43	587.98	217.50
Top	54	100.00	49	561.45	224.47
Ground-LoFi	**186**	**90.86**	**154**	**1040.47**	**392.24**
Back	5	100.00	4	1074.75	140.48
Front	35	88.57	31	984.35	345.97
Left	54	85.19	43	1124.81	377.61
Right	37	97.30	29	1123.41	440.09
Top	55	92.73	47	946.21	402.48
Roof	**150**	**93.33**	**131**	**967.58**	**305.45**
Back	16	93.75	12	1240.25	396.59
Front	43	97.67	40	940.38	261.58
Left	31	87.10	26	976.73	255.95
Right	32	96.88	29	961.97	315.07
Top	28	89.29	24	873.46	307.56
Ground	**249**	**88.76**	**205**	**989.03**	**305.31**
Back	9	88.89	8	1274.25	283.90
Front	56	83.93	44	909.98	245.53
Left	71	92.96	58	1026.07	320.29
Right	60	83.33	46	1031.87	316.76
Top	53	94.34	49	929.39	296.97

Note. Different number of warnings resulted from situational factors inside the VR scene.

These results show that participants had the fastest RTs in the *Baseline* scene, where they could concentrate fully on the vibrotactile cues. In the three VR tasks, the RTs are comparable regarding the accuracy (88.76 – 93.33 %) and the mean RT. A non-parametric Friedman Test has been used to determine whether the differences were also statistically significant. The Friedman Test has shown statistically significant differences in the RT measures between the scenes, $X_2(3) = 21.923$, $p < .0001$, with a large effect size $W = .562$. A post-hoc analysis with a Bonferroni adjustment revealed statistically significant increases of RTs between the *Baseline* measure and each of the three follow-up scenes. In contrast, no statistically significant differences in RT times were found between *Ground*, *Ground-LoFi*, and *Tools*.

Figure 5.19 shows a kernel density plot of the RT distribution among the scenes. The plot shows that the RTs had approximately the same distribution among the three VR scenes in which a secondary task was used, with *Ground-LoFi* showing the widest distribution with the lowest peak.

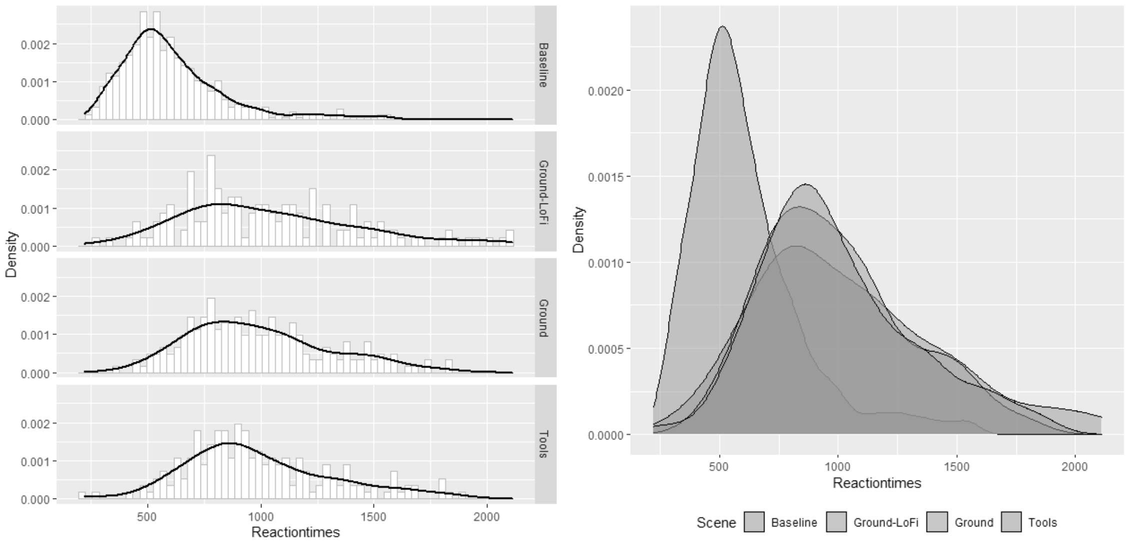

Figure 5.19: Kernel density plots of the RT data of each scene

Finally, warnings with the intensity level ‘high’ were explored for differences regarding the used vibrotactile patterns in terms of duration, repetition, and pauses between vibration cues Table 21. The data found a disproportionate application of pattern 5 due to a misconfiguration in one of the used scripts. However, all applied patterns indicate high accuracy (> 86%), suggesting that vibration patterns using a high vibration intensity are relatively easy to detect in the used VR setting.

Table 21: Descriptive Data for different Vibration Patterns (intensity level 'high')

Pattern	Parameters	Total n	Responded	Accuracy	Final n	Mean	Std. Dev.
1	(100, 50, 3)	41	38	92.68%	37	985.24	351.50
2	(150, 50, 3)	59	51	86.44%	46	1027.89	384.75
3	(200, 50, 2)	10	9	90.00%	8	1124.38	475.59
4	(200, 50, 3)	53	49	92.45%	48	944.19	210.65
5	(200, 100, 3)	326	292	89.57%	271	1010.56	331.31
6	(200, 200, 4)	26	26	100.00%	24	894.38	385.94
7	(200, 600, 3)	36	35	97.22%	31	908.81	323.97
8	(450, 450, 2)	56	56	100.00%	53	601.68	262.11
9	(450, 450, 3)	36	35	97.22%	33	586.24	163.92
10	(500, 500, 2)	57	57	100.00%	49	549.18	156.18
11	(500, 500, 3)	50	48	96.00%	45	587.36	303.21
12	(600, 200, 2)	23	22	95.65%	21	825.00	347.35
13	(600, 600, 2)	32	30	93.75%	27	884.78	336.22
14	(1000, 500, 3)	10	9	90.00%	8	995.75	396.75

Note. Data for all tasks including baseline measure. Parameters = (Duration in ms, Delay in ms, Number of repeating signals). ‘Total n’ refers to the total number of applied cues, ‘Responded’ to the correct reaction to a cue, ‘Final n’ to the total number of applied cues after the RT cleanup procedure.

The data also shows that an increase in delay or repetition does not follow with a higher detection rate of warning signals. For example, comparing patterns 7 and 8, the accuracy for pattern 8 reduced slightly, although the pattern used more repetitions. The same effect applies between patterns 10 and 11. Additionally, comparing the accuracy for patterns 12 and 13, pattern 13, using a longer pause between vibration signals, has a minimally lower accuracy than pattern 12. However, the data differences are marginal, and the dataset is too small to draw general conclusions. In addition, deeper data analysis has shown that the patterns have not been applied equally across all scenes, e.g., patterns 8 and 9 have only been applied in the Baseline measure. Thus, a deeper comparison is impractical at this point. In conclusion, it can be noted that all the patterns applied have a high detection rate, even when filtering out the RT data for the baseline measurement (accuracy above 85%).

Regarding interpersonal differences between participants, a boxplot visualization of the *raw* data (Figure 5.20) for each participant shows that for most participants, the RTs in the three scenes with a task became longer than in the baseline measurement. However, it also shows that P4, for example, had a substantial spread in the baseline task compared to the other scenes.

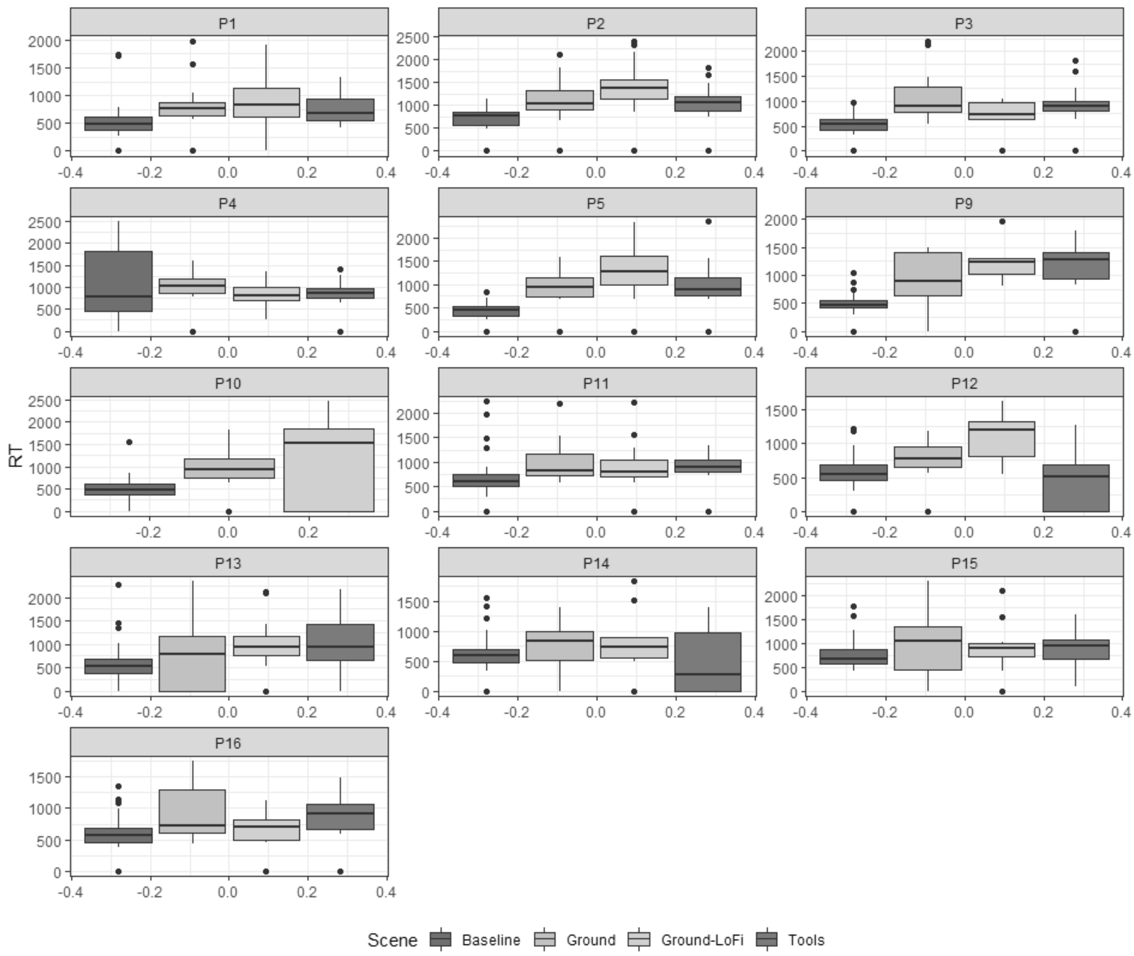

Figure 5.20: Boxplot visualization of participants' (raw) reaction times

For a deeper understanding of the interpersonal differences among the participants, Table 22 shows the summed RT data, accuracy, mean RT, and standard deviation for each participant. The table is based on participants' data across all scenes and vibration cues. The data shows that, on the one hand, the standard deviations are very high, which can be explained by the lack of data sanitization process, as RT distributions are long-tailed. On the other hand, the data reveals that participants needed up to 400ms longer on average to react to vibration warnings. For example, P2 took, on average, 367ms longer than P1 to react to the vibration warnings, but even with a lower accuracy and higher spread. In contrast, P12 and P14 were the fastest on average but had the worst accuracy on vibrotactile warnings.

Table 22: Descriptive (raw) data of vibrotactile responses per participant

PID	Total RT Count	With Response	Accuracy	Mean	Std. Dev.
P1	71	65	91.55	771.62	538.93
P2	94	84	89.36	1139.12	935.23
P3	67	63	94.03	892.40	633.13
P4	178	163	91.57	1047.03	701.43
P5	94	83	88.30	714.31	558.66
P9	85	80	94.12	775.07	601.66
P10	75	68	90.67	707.28	588.30
P11	117	110	94.02	864.87	557.38
P12	88	73	82.95	634.09	490.55
P13	70	61	87.14	1072.80	788.07
P14	105	86	81.90	670.13	546.74
P15	112	107	95.54	907.17	552.41
P16	91	88	96.70	771.19	483.38

Note. This table is based on the raw reaction time data of participants for all four scenes and all vibration patterns, to fully disclose means and standard deviations before any data sanitization process was applied.

5.9.2 Vibration Intensity Levels

In the scenes *Baseline* and *Tools*, the intensity of vibrations changed randomly to other configurations to explore how well users recognize lower signal intensities. While "High" (90-100%) was the most applied of the three levels, the intensities 'Low' (50-60%) and 'Medium' (70-80%) were also randomly used. Intensities lower than 50% of the applied voltage were not used, as they were hardly noticeable. Due to the study’s design, learning effects will have occurred on the RT task between the baseline measure and the scene *Tools*. However, this analysis is only done to explore different vibration designs rather than to compare the mean RT between both scenes, which was already described in Section 5.9.1.

Table 23: Descriptive data of vibrotactile warnings for scenes Baseline and Tools

Scene	Intensity	Total count	With Response	Accuracy	Final count	Mean	Std. Dev.
Baseline	Low	153	117	76.47%	112	648.50	250.48
	Medium	212	209	98.58%	188	599.42	233.49
	High	235	232	98.72%	216	595.58	226.71
Tools	Low	54	36	66.67%	32	1032.38	328.19
	Medium	28	27	96.43%	24	1059.04	389.59
	High	150	140	93.33%	131	967.58	305.45

Note. Final count = Number of RTs used for further analyses after data cleanup.

Descriptive statistics show lower accuracies in detecting vibrations with the intensity level 'Low' for both scenes. For *Tools*, the accuracy is slightly lower than in the baseline measure. The average response time to signals did not change or changed only marginally between the intensity levels *Low* and *Medium* or *High*.

A kernel density plot over all intensities (Figure 5.21) shows that the RTs display a typically skewed distribution with a long tail for the baseline measurement. In contrast, for *Tools*, the distributions differ between all three intensities. Only the density curve for high intensities shows a visible peak at around 900ms (M = 967.58), indicating that, for the high intensity, most RTs were distributed around the mean value. However, the final count of RTs with different intensity levels is much lower in *Tools* than in *Baseline*. An examination of the accuracy showed that vibrations occurring on the left were detected minimally worse (Tools = 74.47%, Baseline = 86.96%). The remaining accuracies were all above 88%.

When comparing the data solely on the repetition parameters, the results have shown the highest accuracy when using four repetitions of the vibrotactile signals (6 out of 6 detected for each scene). However, without any secondary task (in *Baseline*), two repetitions achieved an accuracy of 92.52 % (85.67 % after data sanitization), whereas with a secondary task (in *Tools*), the accuracy dropped to 73.13 % (64.18 % after data sanitization). When the vibrotactile signal was repeated three times, the accuracy was for both scenes higher than 93% (higher than 85% after data sanitization).

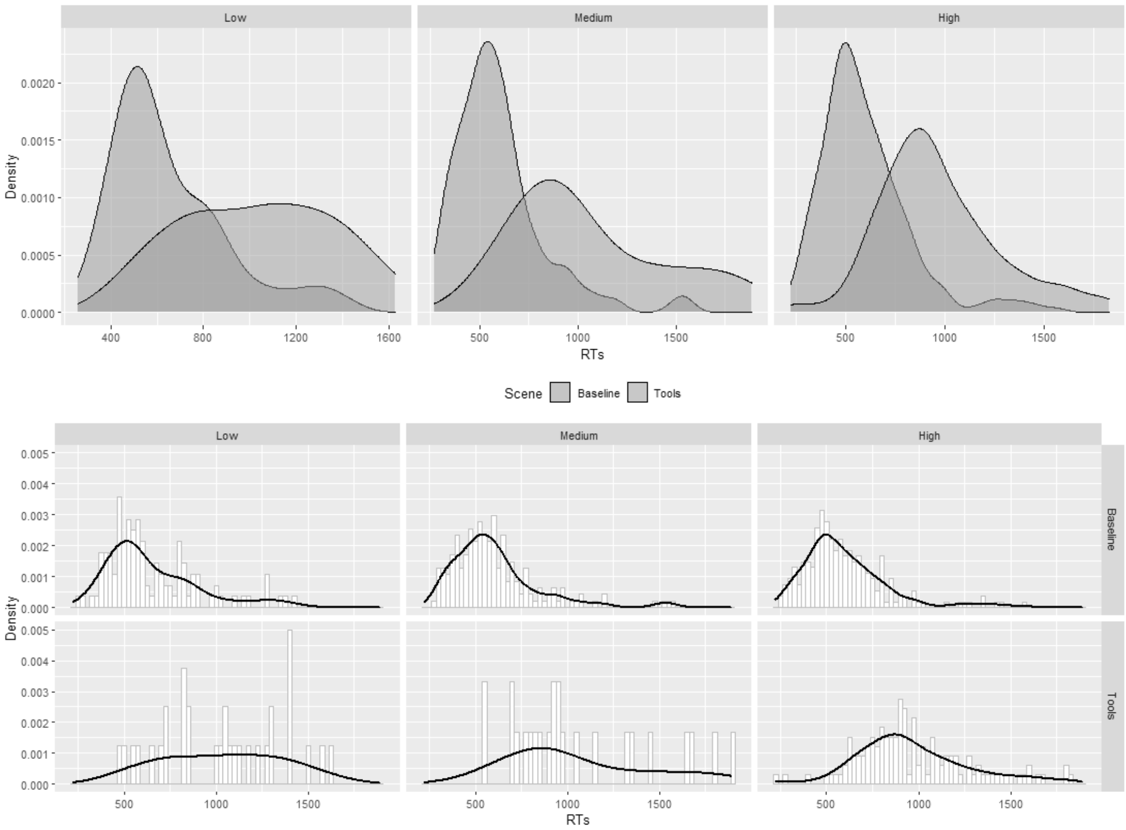

Figure 5.21: Density plots for Baseline and Tools with three levels of intensities

Regarding the duration of vibration signals, the data has shown no apparent impact of the signal length, as the detection accuracy varied among different durations. However, the RT accuracy (after data sanitization) was around 50-58% for vibrotactile patterns that used a low intensity, low duration (100-200ms), only two repetitions, and a pause of 50ms between signals.

5.9.3 Directional Vibrotactile Cues and Wearable

In the interview, participants were asked about the vibrotactile warning signals and the comfortability of the belt. The vibrotactile belt was rated as unobtrusive and did not reduce the freedom of movement. No participant mentioned something negative about its comfortability. One participant summarized it as: "*Yes, you could comfortably wear it. Except for the vibration, you didn't really notice it at all*" (P3). Finally, the body mass index (BMI) was calculated for each participant. The belt has been successfully adapted to and tested with the different BMIs of the participants, ranging from 17.91-22.6 (females) to 20.02-31.86 (males).

Regarding the directional warning cues, participants mentioned that the directional vibrotactile feedback helped to notice hazards: "*in general, I found the vibrations quite good because then you always knew […] from which direction something [a hazard] was coming. Most of the time, I could tell [the direction], but otherwise, I still found it good just to know something [a hazard] was nearby*" (P6).

After finishing the baseline measurement, participants completed a short questionnaire about how they interpreted the vibration signals (Appendix K). The exploratory questionnaire uses five items with an 11-point Likert scale, asking what the vibration signals could mean. Additionally, participants should guess how many vibration motors were used for each direction, which was used to see if they could identify the motors explicitly. As described in Section 2.2.4, multiple vibration points might dissolve to one 'felt' vibration if they are located spatially near each other. None of the fourteen participants guessed the correct number of used motors for each side, whereas there was a tendency for a higher number for the front and rear directions.

The questionnaire also asked how the origin of vibration cues was interpreted. Up to this point, the vibration signals had no meaning to the participants yet. The mean and median values are shown in Table 24, whereas items could be rated between 0-11 (disagree-agree). On average, participants rated highest for interpreting vibrotactile signals as 'touch', followed (on average) by the rating as "an object moving towards one", and "an object in the direction". Both items can be considered to reflect the function of the vibrations in the study. Only after that, on average, the vibration was understood as a hint to move in this direction. However, this interpretation has hardly any explanatory value but was intended to uncover an overall impression which purpose or meaning participants would naturally ascribe to the vibrations before they were explained the actual purpose of the vibration signals used in the study.

Table 24: Mean and median ratings for the interpretation of tactile meaning

Item: The tactile stimulus indicates that…	Mean	Std. Dev	Md
I should move in the direction of the stimulus	5.58	2.56	6
something is moving toward me from the direction of the stimulus	7.42	2.56	8
that there is an object in the direction	7.00	2.61	7
something is touching me at that spot	9.33	1.89	10
is no object in the direction	3.42	2.36	3

Note. n = 12, as two participants already knew the idea behind the vibrotactile signals for this study.

5.9.4 Hazard Recognition

During the semi-structured interviews, participants were asked about the hazards they noticed during the VR scenes. To support their memory of the scenes, they could view a (bird-view) screenshot of the construction site on a monitor.

5.9.4.1 Overview of Recognized Hazards

There are mixed results in the recognition of hazards (Table 25). Hazards that included visual movement were recognized more than 90% of the time (moving vehicles, jackhammer, drilling hammer, and angle grinder), except for the moving cranes which were recognized by around 50% of participants. During the interviews, several participants mentioned that they did not interpret the crane load above as a threat.

Table 25: Count and rate of recognized hazards (during play)

Scene	Hazard Type	Hazard	Total	%
Ground	Moving vehicle	3 moving vehicles	14	100.0
Ground	Clear workspace	Jackhammer working area	14	100.0
Ground	Falling objects	Overlapping wood planks	4	28.6
Ground	Falling objects	Overlapping chainsaw at edge of plateau	3	21.4
Ground	Clear workspace	Drilling hammer working area, falling bricks	13	92.9
Ground	Contact with electr. power	Defective power aggregate (sparks)	11	78.6
Ground	Falling objects	Crane load above	7	50.0
Tools	Falling from heights	Missing fall protection	10	71.4
Tools	Falling from heights	Defective fall protection	**0**	**0.0**
Tools	Falling objects	Falling pipes	3	21.4
Tools	Falling objects	Overlapping material	7	50.0
Tools	Clear workspace	Workers using angle grinder (sparks)	14	100.0
Tools	Falling objects	Crane load above	8	57.1

Note. n = 14.

Regarding other hazards from above (falling objects), most participants did not interpret overlapping materials as threats. Also, many participants did not notice the chainsaw overhanging the edge of a floor or the falling pipes. In the case of the chainsaw, this might have been due to its placement near another worker who was drilling on a plateau. As one participant mentioned: "*I think I didn't notice that [chainsaw] because I thought the vibration was related to the worker*" (P11).

Considering the hazard of falling from heights, most participants did interpret *missing fall protection* as a threat. However, two participants did not notice the holes in the ground of the floor. One of them even asked somewhat in disbelief: "*I didn't notice them, I didn't notice that I was there. So, I didn't even realize that you could fall down. Could you fall down?"* (P1). Regarding the *defective fall protection,* no participant mentioned it as a potential hazard. This assessment can be attributed to the fact that most participants did not even notice the defective fall protection system and, that the participants who did notice it, did not categorize it as a hazard. In the interviews, only two participants mentioned that they saw/noticed the defective fall protection at all, but did not understand it as a threat. Another participant cited the field of view during the VR experience as a reason why he did not recognize the defective fall protection, as he stated, "*When you started to show the static scene in 3D on the screen, of course, I noticed it. So, I saw that* *it also looks not quite kosher. But in the world, immersive, I had not paid attention to this spot*" (P16).

One participant mentioned the visual anticipation of hazards and compared it to his knowledge of video games. He questioned if the frequency of hazards would occur in a real construction setting and said that from a video game point of view, he would understand why so many hazards occurred at once (repetitively). Another participant stated that hazards felt very urgent when the belt vibrated in all four directions (= hazard from above), because it was "*so extreme [that] I thought, oh shit actually I should get out of here now*" (P15).

5.9.4.2 Accident Analysis

One participant was "hit" virtually by a compactor, which, in the simulation, caused the compactor to "drive through the player". The participant mentioned it was difficult to resolve the direction of the vibrotactile warning signal, as this event happened 30 seconds after the first VR scene (after the baseline measure) had started and the participant had difficulties dealing with the controls in the beginning. Reviewing the recorded play video and looking into the log files of the issued vibrotactile warnings of this accident has made it possible to reconstruct the event. The event sequence is shown in Figure 5.22, where the participant

1) sees an *excavator* in front,
2) has difficulties with the interaction and loses a black garbage bag, which falls on the ground,
3) looks to the left to ensure that the excavator is not coming near,
4) turns back to the garbage bag,
5) tries to get the garbage bag,
6) gets "run over" by a *compactor*, a second vehicle that came from the back.

The logs have shown that the participant was warned about the compactor two times before the accident happened. The first warning was around 20 seconds before the accident, which is not shown in the Figure 5.22. Unfortunately, the participant seemed to have forgotten the slowly moving compactor and shifted the attention toward the excavator. Around four seconds before the participant was run over, a second warning was given for an approaching object in the back view of the participant. However, as there were two vehicles around the participant, it may have been that the participant mapped the vibrotactile warning toward the excavator and not toward the compactor. Discussing the event in the post-play interview could not resolve this conclusively. However, the event showed that it would be helpful to have prior training to assess and understand the vibrotactile signals and more extended training with the controls. In addition, it is worth mentioning that the speed of the compactor was relatively slow, and the time sequence from warning to impact was nevertheless only four seconds. Thus, the event also vividly illustrates the complexity and challenges involved in the idea of a proximity warning system.

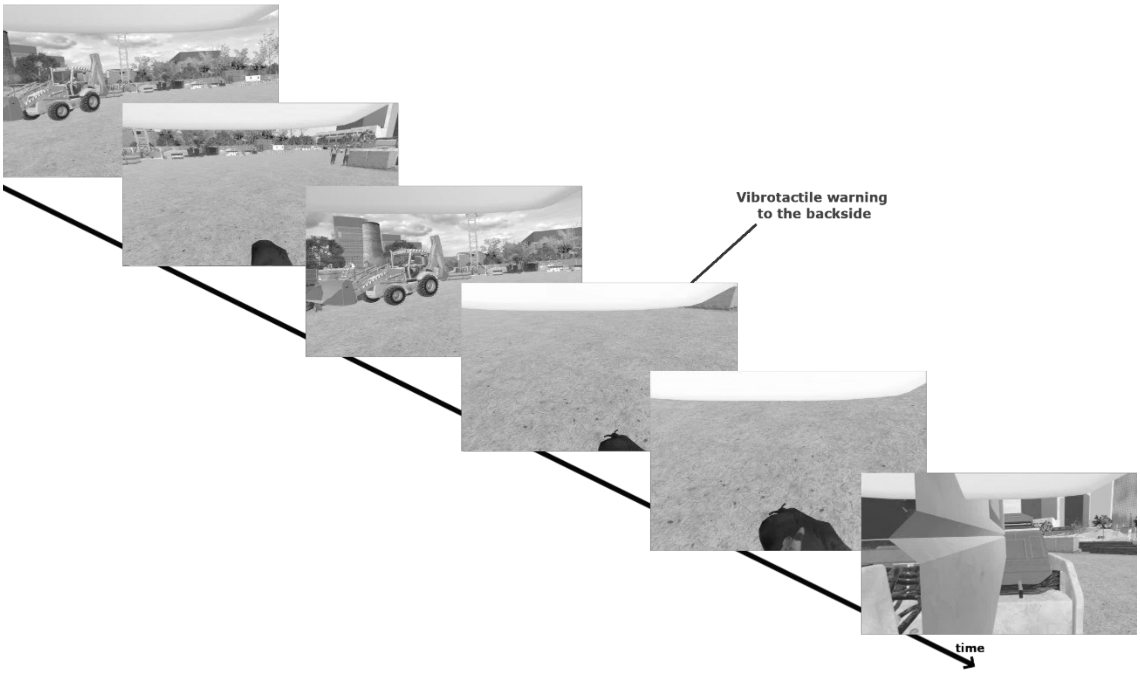

Figure 5.22: Timing of events when a participant was hit by a vehicle

5.9.4.3 Other Objects Interpreted as Hazards

Lastly, six participants interpreted the material lying on the way as slip, trip and fall hazard (Figure 5.23, objects in red circle). It could not be clarified conclusively whether the participants just interpreted the material lying around as a source of threat or whether there occurred vibrotactile warnings in the area due to the worker with the jackhammer and the warning area of the moving vehicles which were falsely mapped as coming from the material. At least two (out of the six) participants argued that they did not interpret it as a real danger, but one of those two participants clarified that he had to be "*careful around the material"* (P2). Also, both participants who experienced the VR scenes without vibrotactile belt interpreted the material on the ground as a potential hazard.

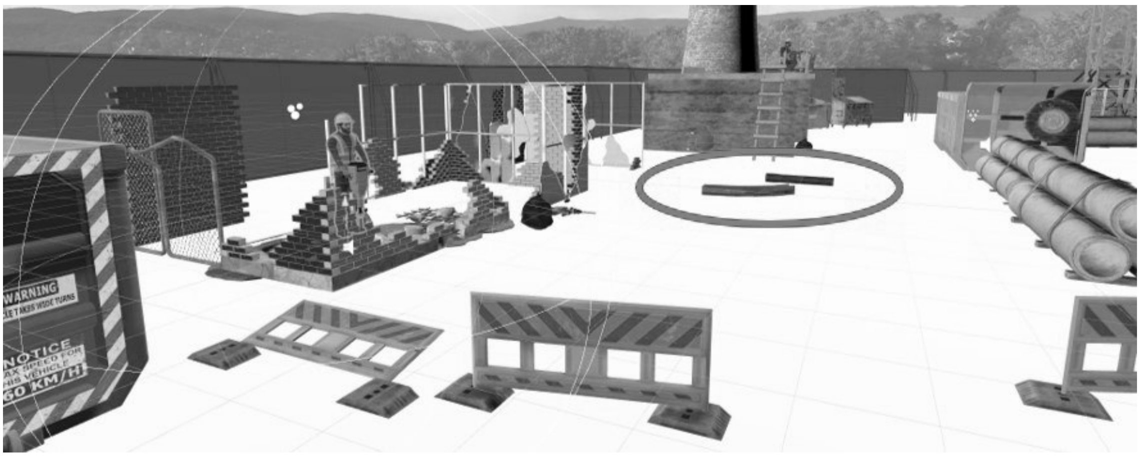

Figure 5.23: Steel beams interpreted as hazards

5.9.5 Task Descriptions and Controls

In general, participants felt the task was very easy to solve. According to the participants, the only challenge within the simulation was the initial orientation within the VE and finding out where the objects had to be placed. However, most of the participants initially struggled with the controllers, as the controllers were used for the movements in the VE, interacting with objects, and reacting to vibration warnings. One participant described it vividly: "*At the beginning it was very overwhelming, because then it suddenly vibrated and I had to press it [the response button] at the same time. But I had the garbage bags in my hand at the same time and then I didn't find the button and then let go of the garbage bag again. That was a bit overwhelming*" (P3). However, every participant assured that it took only a little time to get used to at the beginning, and the difficulty quickly dissipated.

On average, participants were 15 minutes in the VR scenes, whereas a slightly reduced playtime between the first and the third scene was observed. Reasons for the reduced playtime were learning effects, as the aforementioned 'initial orientation' dissolved quicker and less time to explore the VE visually. Mean times for the first scene were M = 6:02 min (Md = 6:06 min), for the second scene M = 4:21 min (Md = 4:33 min), and for the third scene M = 4:34 min (Md = 4:08 min).

During the interview, fifteen participants stated that they found the task inside the VE as 'realistic'. In contrast, five participants specified the task more precisely as 'at least not unrealistic' and that one probably would not walk across the site to collect garbage bags. However, getting and bringing materials and tools would be a regular site activity. One participant mentioned that the task felt unrealistic but added that walking between multiple points in a construction setting is a typical task and stated, "*so if you really had to go back and forth to actually get stuff, I can understand the idea behind*" (P14).

5.9.6 Workload and Task Difficulty

The overall workload was assessed with the Nasa-TLX that participants did four times during the study: after the baseline measurement and after each VR task (*Ground, Tools, Ground-LoFi*). Regarding the mental demand, participants perceived the VR scenes *Ground* and *Tools* as most demanding, followed by the graphically simplified version *Ground-LoFi*. All scenes were rated as more mentally demanding than the *Baseline* measure, where participants had to only do the reaction time task. Differences can also be seen in the scale physical demand, as participants could stand still during the baseline measure, whereas in the other three VR scenes they had to turn their body and heads or even bend over to pick up objects. Regarding their performance, participants rated their performances on average minimally worse during the Baseline measurement (M = 34.17, SD = 15.50) compared to the other VR scenes (see data in Table 26).

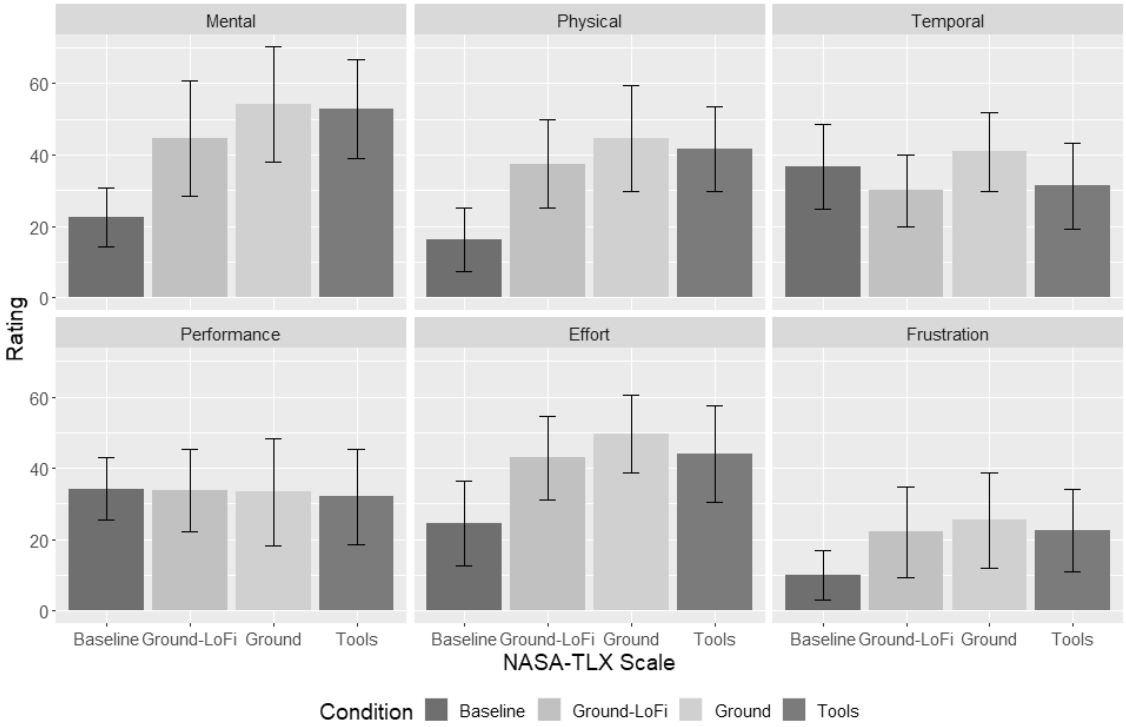

Figure 5.24: Bar chart of TLX ratings for each VR scene grouped by scale

Participants rated the VR scene *Ground* as the most demanding for the overall workload, followed by *Tools*, *Ground-LoFi*, and *Baseline*. However, a non-parametric Friedman test has revealed no significant differences between the perceived workload in all conditions, $X^2(3) = 7.4$, $p = .06$.

Table 26: Nasa-TLX ratings for the VR tasks

		Mental	**Physical**	**Temp.**	**Perf.**	**Effort**	**Frust.**	**OW**
Baseline	Md	25.00	12.50	32.50	30.00	20.00	7.50	20.00
	M	22.50	16.25	36.67	34.17	24.58	10.00	24.03
	SD	14.54	15.83	21.03	15.50	20.94	12.06	18.87
Ground-LoFi	Md	37.50	40.00	22.50	27.50	42.50	17.50	32.50
	M	54.17	44.58	40.83	33.33	49.58	25.42	35.14
	SD	28.51	26.06	19.40	26.40	19.12	23.59	22.74
Ground	Md	42.50	35.00	47.50	32.50	50.00	22.50	35.00
	M	44.58	37.50	30.00	33.75	42.92	22.08	41.32
	SD	28.40	21.69	17.71	20.57	20.83	22.41	25.20
Tools	Md	57.50	40.00	22.50	25.00	40.00	15.00	30.00
	M	52.92	41.67	31.25	32.08	44.17	22.50	37.43
	SD	24.35	20.82	21.55	23.59	23.92	20.28	23.87

Note. $n = 12$; Columns: Mental = Mental Demand; Physical = Physical Demand; Temp. = Temporal Demand; Perf. = Performance; Frust. = Frustration; OW = Overall Workload; Rows: Md = Median; M = Mean; SD = Standard Deviation.

Regarding the subscales, a Friedman test on the scale *Mental Demand* has shown statistically significant differences regarding the perceived mental effort of participants, $X^2(3) = 17.15$, $p < .001$, with an effect size of *Kendall's W* = .477, which can be considered as moderate. A post-hoc Signed Rank test with a Bonferroni adjustment on the pairs has shown that the perceived mental effort increased significantly between the *Baseline* measurement (*M* = 22.5, *SD* = 14.5, *Md* = 25) and *Ground* (*M* = 54.2, *SD* = 28.5, *Md* = 42.5), *p* = .012, as well as between the baseline measurement and *Tools* (*M* = 52.9, *SD* = 24.4, *Md* = 57.5), *p* = .006. No statistically significant differences were found between the remaining pairs.

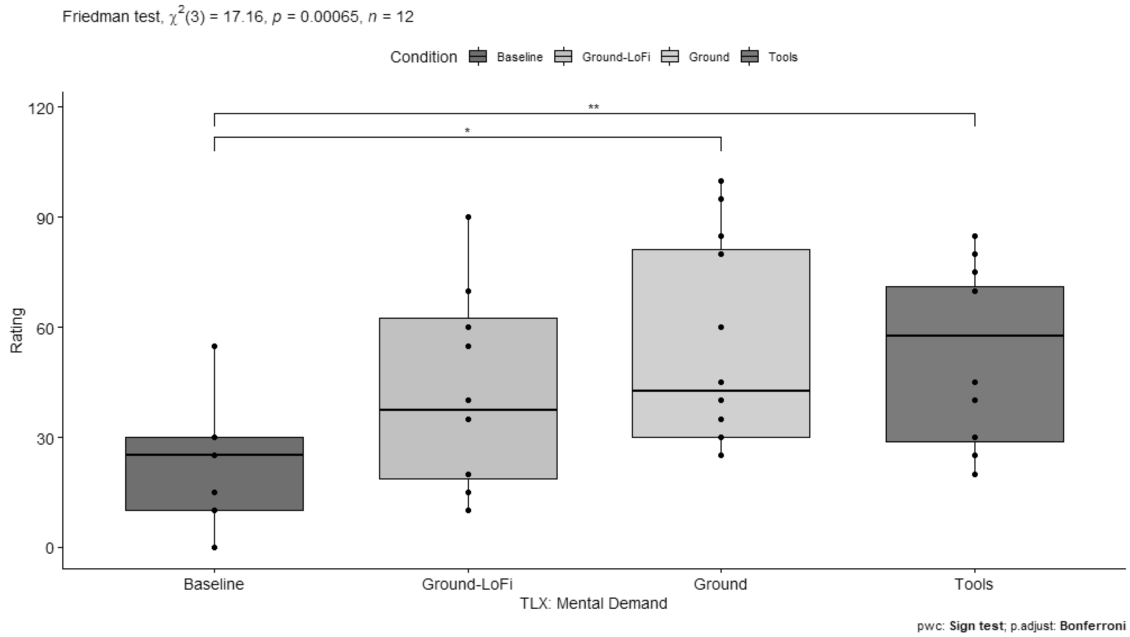

Figure 5.25: Friedman test on the TLX-scale 'Mental Demand'

For the scale *Physical Demand*, a Friedman test has also shown statistically significant differences in the perceived physical effort, $X^2(3) = 17.15$, *p* < .001, *Kendall's W* = .476. The post-hoc signed rank test hast shown significant differences in the perceived physical effort between Baseline (*M* = 16.2, *SD* = 15.8, *Md* = 12.5) and the Ground scene (*M* = 44.6, *SD* = 26.1, *Md* = 35), *p* = .006, as well as the Tools scene (*M* = 41.7, *SD* = 20.8, *Md* = 40), *p* = .012.

5.9.7 Virtual Environment and Graphical Representation

Regarding the visual representation, it was hypothesized that the graphically more sophisticated version increases perceived mental demand and overall workload, as participants would have to process a visually more dynamic and complex environment. The TLX ratings have been compared between *Ground-LoFi* and *Ground* with a non-parametric Wilcoxon signed-rank test. The sequence of both VR scenes was counterbalanced between the participants in the study.

A pairwise comparison between the perceived overall workload, measured with the Raw-TLX, has shown no statistically significant increase between *Ground-LoFi* (*Md* = 29.6) and the graphically more sophisticated version *Ground* (*Md = 39.2)*, *Z* = -1.35, *p* = .094. However, there was a statistically significant increase between *Ground-LoFi* (*Md* = 25) and *Ground* (*Md* = 35) in the perceived mental demand of participants, *Z* = -1.89,

$p = .029$. Additionally, statistically significant increases for *Ground* could be found in the scale Physical Demand, $Z = -2.04$, $p = .019$, and Temporal Demand, $Z = -2.20$, $p = .012$. These results suggest that in the more sophisticated version of the *Ground* scene, participants felt they needed more mental capacity to solve the task, felt more time pressure to complete the task, and more physical activity to complete the task.

The RT data showed that the total number of logged vibration warnings was, on average, lower in *Ground-LoFi* ($M = 11.8$, $SD = 6.38$) compared to *Ground* ($M = 15.8$, $SD = 6.73$). However, the RTs in *Ground-LoFi* were slower on average ($M = 1040.47$, $SD = 392.24$) than in Ground ($M = 989.03$, $SD = 305.31$), thus, contradicting the TLX results.

Participants were asked how they experienced the graphics in the interviews. All participants felt that the scenes *Ground* and *Tools* seemed more realistic than the low-fidelity version of *Ground*. One participant highlighted the subjectively felt time pressure in the realistic versions: "*Well, I felt rushed because of the noises and because of the graphics, because it was really [like] a [real] construction site*" (P10). Another participant specified that the scenes felt realistic but were far from reality: "*From my point of view, that is, from what I saw, I found it somewhat realistic, that is, not 100%, because the graphics are of course not exceptionally good*" (P11).

Regarding the hazard recognition and the perception of hazards in the two scenes, one participant compared both versions of the *Ground* scene, stating that hazards could be seen more quickly in the low-fidelity version: "*I think it makes you see, I don't know, a little clearer, because it looks very simplified, unlike that [other version]. That's why I found it more relaxed in terms of virtual reality, more like a Mario Kart game or something. [...] So, I noticed the objects on the ground more easily, so you can already see them [in advance], they look more isolated, easier to recognize. Yes, a little bit, in any case. That [to recognize hazards] makes it a little easier.*" (P14).

5.9.8 Presence and Realism

The iPQ and the statements in the interviews were reviewed to analyze felt presence. The iPQ includes 14 items to assess the general presence, the spatial presence (five items), the involvement in the scene, and the experienced realism (Table 27).

Table 27: iPQ scales: means, standard deviation and median

	PRES			SP			INV			REAL		
Scene	**M**	**SD**	**Md**	**M**	**SD**	**Md**	**M**	**SD**	**Md**	**M**	**SD**	**Md**
Baseline	4.08	1.21	4.04	4.80	0.59	4.80	3.33	1.16	3.29	2.88	1.12	2.82
Ground	5.07	0.83	5.00	4.84	0.99	5.00	4.68	1.02	4.75	3.59	1.05	3.75
Ground-LoFi	4.50	0.94	5.00	4.50	0.88	4.40	4.04	1.56	4.00	2.82	1.04	2.88
Tools	4.93	1.00	5.00	4.73	0.81	4.60	3.88	1.73	3.88	3.46	0.96	3.25

Note. PRES = General felt presence, SP = spatial presence, INV = involvement in the scene, REAL = experienced realism. Ratings shown are mean (M), standard deviation (SD), and median (Md).

Mean iPQ ratings are displayed in Figure 5.26 for each condition grouped by scale (left) and for each scale grouped by condition (right), with ratings from 0-6 (worst to best, with

3 as neutral rating). The descriptive data regarding experienced realism (REAL) shows that participants rated the *Baseline* scene and the *LoFi*-Scene as more or less unrealistic compared to *Tools* and *Ground* were rated as rather realistic. Regarding the felt spatial presence (SP), no fundamental differences can be seen among the scenes. Even the baseline measure got high ratings for SP, indicating that the spatial presence can be attributed to the VR hardware and not the experienced scene. For the involvement in the scene (INV), *Ground* was rated slightly higher than *Ground-LoFi* and *Tools*, indicating that participants experienced this scene as most interactive and immersive. Last, the overall felt presence (PRES) was rated high for all three VR-tasks and slightly higher than in the *Baseline* measurement. A non-parametric Friedman Test was computed to compare the ordinal ratings among all four conditions to perform a statistical analysis.

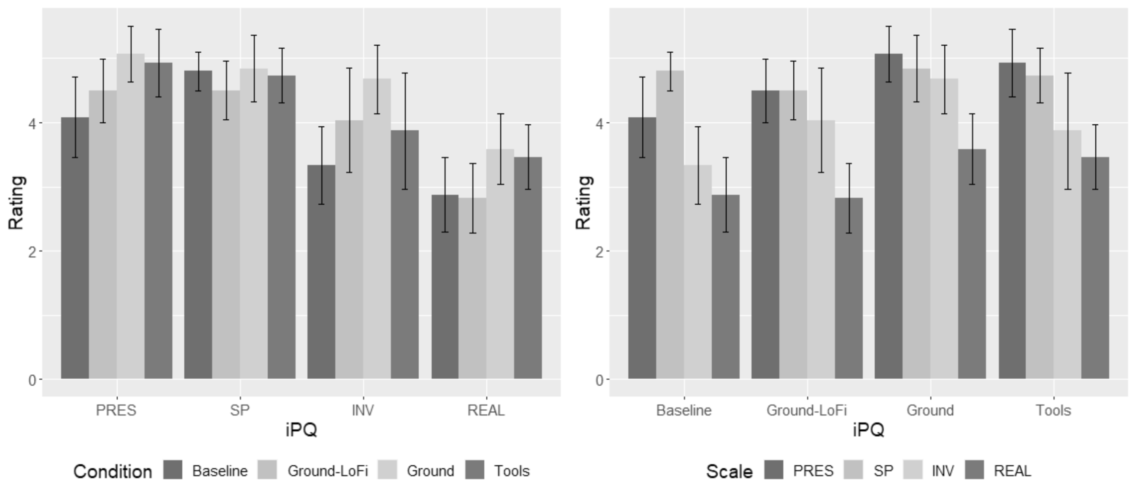

Figure 5.26: Mean ratings for the iPQ

The Friedman tests did not reveal statistically significant differences between the spatial presence (SP) among conditions, suggesting that in all four VR scenes, participants felt isolated from the real environment. For the general felt presence (PRES), the test revealed statistically significant differences $X^2(3) = 12.78$, $p = .005$, with a moderate effect size $W_{\text{Kendall}} = .304$. A Conover's post-hoc pairwise comparison revealed significant differences between *Baseline* and *Ground*, $p = .015$, and between *Baseline* and *Tools*, $p = .047$. For the experienced degree of involvement in the virtual scene (INV), a Friedman test revealed statistically significant differences $X^2(3) = 19.98$, $p < .001$, with a moderate effect size $W_{\text{Kendall}} = .48$. A Conover's post-hoc test revealed a statistically significant difference only between the *Baseline* measure and *Ground* ($p < .001$) for the experienced involvement. On the scale experienced realism (REAL), a Friedman test revealed statistically significant differences $X^2(3) = 11.88$, $p = .008$, with a small effect size $W_{\text{Kendall}} = .28$. A Conover's post-hoc pairwise comparison revealed only significant differences between the scenes *Baseline* and *Ground* ($p = .045$).

Participants were also asked about the degree of realism, the visual representations, and the soundscape during the semi-structured interview. Regarding the experienced degree of realism, the participants all confirmed that the *Ground* scene with the better textures was seen as more realistic than the *Lo-Fi* version.

Also, if noticed, specific details in the VE were perceived as adding to the degree of realism. For instance, one participant highlighted the signs on the cars, the vehicle assets and that the same construction setting was used for the scenes *Tools* and *Ground*: "*but with the last one [Scene: Ground] I thought that was quite cool, that the circle then closes and then with the buildings and the different vehicles that then had the details like signs, I thought that was then very realistic*" (P5). Other details mentioned in this sense were the airplanes when participants noticed them (described in more detail in Section 5.9.9).

Whereas the environment was perceived as realistic, the construction workers were not. As one participant stated: "*especially the construction workers, they didn't appear so very human. You could just perceive that, but otherwise I felt like I was in a real construction site*" (P4). Another participant specified that most of the construction workers were not moving but standing around, which was rated as unrealistic. In this regard, two participants would have liked to see social extensions in the scenarios by having to work on a task with other workers. One participant wanted to interact with other workers: "*there were a few people who were working on something somewhere. So that I would have to take something away from them or clean something up or bring them something. Because honestly, I didn't feel like a co-worker*" (P13). Another participant added other examples that could add to a more social experience in the VR scenes: "*Would have been cooler if you could interact with the people, but otherwise it was all good. I must say that it was very close to reality. […] But in any case, that you could talk to them. Or, for example, when a truck drives by say, hey, I'm going to pass that way. Or maybe that something could be repaired [by you]*" (P14).

Finally, regarding the applied soundscapes to create the VR scenes, thirteen participants stated that the sounds also added to the perceived realism of the site setting and that the sounds suited the setting. Eight participants mentioned that they heard surround sound and could determine the direction of sounds accordingly and hear if sounds got louder or quieter depending on the distance to the source. For instance, one of the experts (P1) stated: "*it (the sound) was pretty good actually. You could also, like I said when the pipe fell down locate where that was. [With the] Jackhammer too. So, the sound was pretty good. So, I thought it was nice that it was so continuous and that there was a certain noise level, so that was good*". Another expert (P16) mentioned that he was surprised how well the sound and the hardware added to the overall experience: "*the sound in combination with the headset, which has very good headphones and cuts you off from the outside world very well*". The loudness of sounds was highlighted by several participants. For example, when asked about the soundscape, P13 stated: "*Oh, it was realistic. It was also loud and I would say that was actually very realistic under the circumstances. You had told me something and I couldn't hear it. And that would happen on the construction site as well. So that was really realistic*". However, all participants ensured that the sound was not too loud during the study.

Regarding the cable-based setup of the VR headset, five participants mentioned that the cable did somewhat disturb their feeling of presence. As P3 noted: "*you always turn [your body in VR] automatically and then I always noticed that this cable twisted around me.*

that's what I noticed, that always called me back into the real world a little bit, so to speak". Another participant (P13) also noted the possibility of a tangling cable and also outlined the cons of wireless kits: "*Yes, I think the cable bothers you especially when you have no experience with VR. Then you overestimate the danger of the cable. But the danger is actually there, so if you get so tangled up, then that's bad. There are also wireless kits where you don't have a cable anymore, but I had problems with the frame rate, because then the game stutters a bit*".

5.9.9 Attention to the Environment

Three object types were added to the scene that did not impact the tasks but were added to create a more suitable construction environment overall. For example, the participant's avatar wore a helmet during the scenes. Eight out of 16 participants mentioned noticing the helmet, whereas the other half did not. However, it is worth highlighting that the participants did not have to put the helmet on themselves, but it was already on their heads at the beginning of the scene.

Regarding the two airplanes, only four of the 16 participants noticed them. It resulted from a coincidence for at least one participant, who got warned of a crane load hovering above him and then looked up. One participant mentioned that the airplane increased the overall realism of the scene. Another stated, "*I also saw that there was an airplane at the top of the second one [scene]? That was really cool, I thought it was good*" (P1).

Regarding the traffic surrounding the construction site on two sides, only five of 16 participants did notice the roads with the traffic. Participant P11 stated: "*I noticed all the cars that were driving outside the construction site, that was indeed realistic, and the sounds were also realistic to some extent*". However, as eleven participants did not notice the traffic at all, it seems like they were concentrating on the task and not on the surrounding environment, as one participant stated: "*I didn't pay attention to the surroundings at all, but really focused on the task at hand, so I wasn't nervous, I would say, but I really focused on collecting these garbage bags, so I didn't pay too much attention to the cars*" (P2). This is particularly noteworthy when considering, that during the scene *Tools,* it was quite easy to see and notice the streets from multiple viewpoints (an example shown in Figure 5.27). One participant mentioned time pressure as relevant factor: "*I was so under time pressure somehow that's why I didn't pay attention to it, but yes that's why I didn't see the road*" (P1). Several participants mentioned that time pressure came naturally, although they were never told to do the tasks as quickly as possible. Only one participant (who did not use the vibrotactile belt) actively explored the VR environment after completing the tasks. Since all participants who used the vibrotactile belt were told to respond to the vibration as fast as possible, this may also have called up the feeling of time pressure in them. However, it is impossible to clarify this conclusively.

Figure 5.27: Traffic visible from the roof of the construction shell in the scene 'tools'

5.9.10 Motion Sickness

To assess any signs of motion sickness, participants filled out the Simulator Sickness Questionnaire (SSQ) prior to the testing ('pre') and directly after the tests ('post'). The questionnaire uses 16 items and computes values for the scales nausea, oculomotor disturbance, and disorientation, as well as a total score. Participants were also asked about motion sickness symptoms at the beginning of the semi-structured interviews. The results for the SSQ have been computed and are reported with median values, as suggested in a publication by Bimberg et al. (2020), using the original calculation by Kennedy et al. (1993).

Table 28: Mean, Standard Deviation and Median for the SSQ Scales and Total Score

	Pre			**Post**			**Wilcoxon Signed-Rank (paired)**	
	Mean	SD	Median	Mean	SD	Median	Sig.	p
Nausea	2.04	4.06	0.00	10.22	12.10	9.54	*	.028
Oculomotor Disturbance	4.87	10.13	0.00	10.83	8.78	7.58	ns	.082
Disorientation	3.98	8.51	0.00	19.89	20.22	13.92	**	.006
Total SSQ Score	4.27	7.17	1.87	14.69	10.32	14.96	**	.003

Note. $n = 14$; *ns* = not significant; * = $p < .05$; ** = $p < .01$.

The SSQ results have shown an increase for all subscales and the total score from pre-testing ($Md = 1.87$) to post-testing ($Md = 14.96$). A Wilcoxon signed-rank test for paired samples determined a statistically significant increase in nausea ($z = 2.20$, $p = .028$), in disorientation ($z = 2.75$, $p = .006$), and the total score ($z = 2.96$, $p = .003$). No significant differences were found in oculomotor disturbance ($z = 1.74$, $p = .082$). These results suggest that the exposure to the VR simulations had a negative effect on the subjectively rated participants' overall well-being (total SSQ score). The results also show that participants experienced symptoms of nausea and disorientation. However, at the beginning of the interviews, only six out of 16 participants stated that they felt symptoms like slight nausea. One participant stated that he felt symptoms during the last simulation, whereas another mentioned slight symptoms during the first two simulations. None of the participants felt the need to stop participating in this study, although they were encouraged by the study facilitator to stop their participation whenever they experienced symptoms of motion sickness. Of both experienced participants (‘experts’), one felt no motion sickness symptoms at all, while the other tried to describe his state when rejoining the real environment after the VR experience: “*It's hard to describe, it's a strange feeling, but not necessarily discomfort. So, I wouldn't put it in the category of motion sickness, but you almost have to find yourself again moment in the real world like that.”* (P16).

5.9.11 Usability and User Experience

Participants rated the overall system on average with a SUS-score of 77.32 (*SD* = 7.17), which can be interpreted as ‘good’ and acceptable score (Bangor et al., 2009). During the interviews, participants stated that the system’s usability was generally good, but they did find it challenging to reach the response button on the VR controllers, as it was located above the touchpad. In comparison, the two participants who did not use the vibrotactile belt rated the system with *M* = 93.75 (*SD* = 1.25), which translates to ‘excellent’ usability, even though both participants had no prior experience with using VR systems. During the interviews, no participant stated that the belt was disruptive in any way. Therefore, the results suggest that the lower usability ratings were mainly due to the way one had to react to the vibration warnings.

Regarding the UX, one of the VR experts mentioned a positive UX for the two visually sophisticated scenes (*Tools*, *Ground*) and stated that he felt completely immersed in the environment by highlighting the isolating capacities of the VR headset and the graphics. Additionally, he highlighted the occurrence of the airplane in one of these scenes, as it gave a nice touch to the whole experience. The expert also compared the used scenes to his gaming experiences by saying: “*No, so quite honestly I found the thing is, currently it's just so that there is a strong difference between current games that are not VR and games that are VR. And the thing is this gap is closing little by little, but that's why I can imagine that now, people who have never used VR, say 'yo this is much worse’ and so. I just know that that's about the maximum you can do right now. Sure, you can compare it with [games like] Half Life Alyx and then [the simulation is] just not [good] anymore, but that's also because they have [a budget of] several millions, but I think that [the simulation] is pretty good actually.” (P1).* In total, each participant mentioned that they had a good experience or even fun doing the study.

5.10 Discussion

In this section, the most relevant study results will be discussed in a more general view and are categorized into 1) the evaluation of vibrotactile warnings in VR, 2) hazard recognition, 3) the task design and task workload, and 4) the design of VEs.

5.10.1 Evaluating Vibrotactile Warnings in VR

Participants were able to interpret the directional vibrotactile warnings and changed their behavior on some occurrences, for instance, when warned before a crossing vehicle. However, there was a mix of behavior changes on static and mobile hazards. Whereas mobile hazards such as vehicles were considered every time, a habituation effect on static hazards has formed. Several participants stated that they were able to anticipate the hazards after walking past them a few times and only reacted but did not look around. Such habituation effects could possibly be prevented in VEs if, for example, when static hazards are being cleared away or new hazards occur during the scenario. As another example, an unsecured roof edge could be secured after it has been passed. Such dynamic changes of the static surroundings during play could prevent anticipation of warning signals.

Regarding the evaluation of vibrational patterns, changes in three intensity levels had been investigated. The results suggest that the intensity level only affects the detection rate and not the RT (Section 5.9.2). However, the data shows only slight differences between the intensities medium and high, suggesting that the medium intensity was sufficient to detect signals during the tasks. On a general notice, for warning purposes it should be considered to use stronger intensities anyway to prevent collisions. However, follow-up studies could investigate even more intense vibration signals and examine interpersonal preferences.

On the parameter of vibration repetition, the results suggest that vibration cues should be repeated more frequently rather than less frequently to achieve a higher detection rate. However, in the event of a hazard, too frequent and too long repetitions for the threat from one side may mask another emerging hazard from another side. Hence, the signals should only be repeated for a short time. The parameter duration has shown that very short signals (shorter than 200ms) with short pauses (50ms) resulted in the lowest accuracy.

Another factor noticed during the data analysis is the differences in interpersonal RTs among the participants. The two fastest participants had the lowest accuracy, but participants with slightly higher accuracy needed almost half a second longer to react on average. The approach of using a VR Lab has made it possible to reveal such interpersonal differences while considering the (virtual) contextual work environment. Thus, further studies in VR Labs could study interpersonal differences and adjust individual vibration configurations of warning systems accordingly, especially when participants have a low accuracy noticing the warnings.

In conclusion, the vibration warning system still led to one "accident" in VR, although the participant was warned on time. Since this happened to a participant at the beginning of the first construction VR scene, it can be pointed out that using such warning systems might need training before being used on real construction sites. VR Labs can be used to train the use of such vibrotactile systems.

5.10.2 Hazard Recognition

Hazards with a visual representation (vehicles, crane load, sparks) were identified as a hazard as soon as a vibration warning was issued or even earlier. In particular, mobile hazards were recognized rather quickly, as well as other workers (cutting with an angle grinder, using a jackhammer). However, participants did not understand some hazards as potentially dangerous.

In the case of missing objects, such as the absence of fall protection, some participants did not realize that the vibration warning indicated the absence of fall protection (and thus an unsecured fall edge). Then, there were hazards that participants did not interpret as a threat, although they had to walk beneath them. For instance, pipes, construction wood, or even a chainsaw overhanging the edge of a roof. One explanation for the case of the chainsaw is that it was located near another worker using a drilling hammer and that participants related the warnings toward the worker, not the overhanging chainsaw. Another explanation is that the scaling of the chainsaw was too small, or the textures did not clearly distinguish it from the surroundings. However, for the overhanging material, participants mentioned that it did not look like a threat. Here, participants probably needed more expertise in which objects should be considered as hazards and which not.

A similar situation arose with the fall protection systems. In some cases, participants did not notice that planks were defective or missing from the fall protection system. In this example, construction workers with appropriate expertise might react differently than the study participants (university students). VR Labs allows teaching what hazards people need to be aware of on construction sites without putting themselves in real danger. However, some participants did not even notice floor openings on the ground with missing fall protection, which indicates that this could also have been a visualization problem in the scene.

5.10.3 Task Design and Workload

Overall, participants did not question the pick-and-place task. However, they also pointed out that picking up and transporting away objects and materials is a quite typical task on construction sites. The task was not considered very demanding but was understood as a means to an end and forced participants to walk across the construction site. Therefore, such tasks can also be found in the literature on VR construction work as a simple application example (e.g., Hilfert & König, 2016).

The results revealed no statistically significant differences between the overall perceived workload between the three construction VR scenes. Regarding the VR scenes' high- and low-fidelity versions, the TLX results showed a higher mental demand on average for the high-fidelity version, although no statistical significance was reached. These results support findings in the literature on the graphical fidelity of games having no significant changes in the perceived workload of players, as presented by Gerling et al. (2013). However, participants mentioned in the interviews of the study that they perceived the two VR scenes with the graphically more sophisticated VE as more mentally demanding than the scene with the low-fidelity graphics, as the low-fidelity version allowed an easier overview of the scene due to missing textures and, thus, an easier anticipation of hazards.

5.10.4 Virtual Environment Design

The VE was rated as plausible and realistic. When participants noted details, they were understood as adding to the overall realistic scenery and increasing the overall UX. However, the details went unnoticed with many participants as they were focused on the task and the hazards in the environment. Only one participant actively asked if there was a time limit and if he could explore the surroundings. This result suggests that details can be omitted because they are rarely noticed, and with time pressure, the focus is very much on task completion.

According to the iPQ results, overall presence and experienced realism were higher for the graphically more sophisticated scenes *Ground* and *Tools. P*articipants confirmed in the interviews that these looked much more realistic than the *LoFi*-version. However, the comparisons on the iPQ data did not reach statistical significance. In contrast, a study by Hvass et al. (2017) reported that a higher degree of visual realism led to stronger sensations of presence. In their study, the authors also reported that a higher degree of realism led to stronger fear responses of participants. Therefore, VR Labs should create a high degree of visual realism in the VR scenes, even if this degree may not be necessary for every use case.

5.10.5 Limitations

The study has several limitations. First, the pick and place task of objects to be performed on the virtual construction site was relatively simple, which created hardly any mental stress on its own, except for the felt time pressure. While none of the participants questioned the task but accepted it as a given, it is reasonable to assume that construction workers would have criticized the task in its degree of realism. However, the task ensured that all participants (even those without prior experience in VR) were able to perform it without feeling overwhelmed by the overall setting.

Another limitation relates to the vibrotactile warnings, as they were applied only via a belt around the waist. Follow-up studies should compare vibrotactile feedback among other body parts, for instance, the upper body (e.g., Schultheis, 2015) or the head, as proposed for the bicycle collision warning prototype *TactiHelm* (Vo et al., 2021). In addition, only vibrotactile feedback was used. With the flexibility of VR Labs, vibrotactile feedback could easily be evaluated against other unimodal or multimodal feedback.

Also, the occurrence of a warning from one of the five different directions was displayed binary (on/off). Thus, it was not investigated what effect, for example, cascading signals would have made on hazard detection and handling. For example, two warning areas (collision points) could be used, a first one for a primary vibrotactile warning (as an indicator), and a second, more urgently perceived, vibrotactile warning for an immediate action prompt (Figure 5.28). Such cascading warnings could also be designed using different vibrotactile pattern parameters. With a VR Lab, such patterns can easily be configured and evaluated.

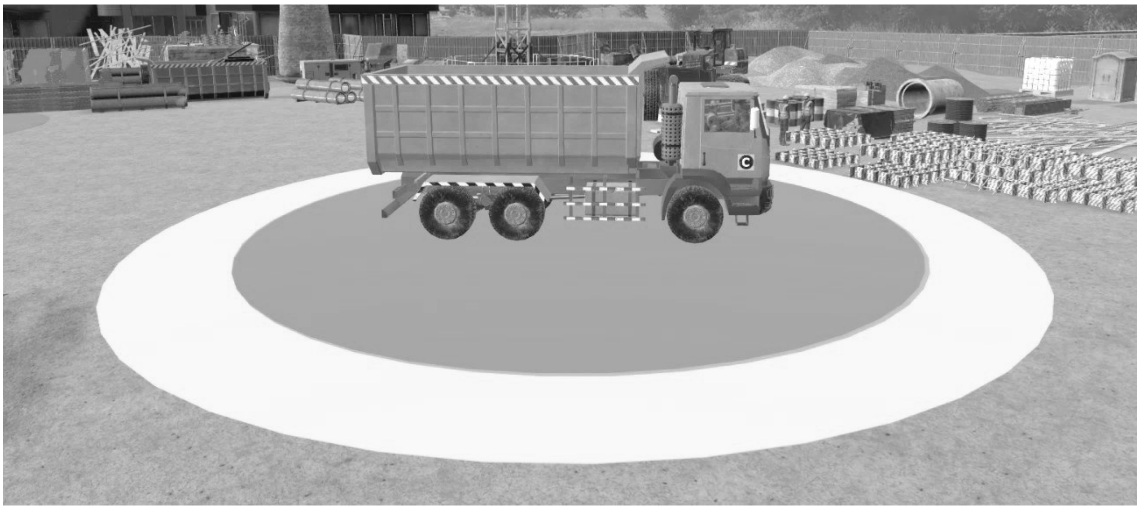

Figure 5.28: Two-level detection zone for a cascading warning system

Last, the number of participants, with a total of 14, is relatively small to draw representative conclusions. Additionally, since the participants were students and had no experience in construction site work, this aspect limits the quality of statements made regarding the realism of the setting and the hazardous events depicted in the scenes. Furthermore, due to the exploratory approach and the large number of different parameters tested, the total number of data sets made for each vibration pattern is small.

5.11 Summary

This chapter presented a study in which the VR Lab was used to test directional vibrotactile warnings. Overall, it was shown that the vibrotactile alerts helped participants to recognize hazards and, in some cases, led to short-term behavioral changes. The study has provided guidance on design aspects of VE and task design in VR simulations.

What notably emerged from this study was that several hazards were not perceived as such and that an accident occurred. Based on these results, it should be determined whether and to what extent VR Labs can be used for learning safety aspects. In the following chapter, such VR safety training is presented for the use case of working with angle grinders.

6 Virtual Reality Safety Training

This chapter[19] discusses the extent to which VR-based safety training is suitable for learning safety knowledge and how participants rate such safety training. The contents of this study were developed as part of the research project *DigiRAB* (see Section 3.1).

6.1 Research Objectives

One method to try to reduce accident numbers in the construction industry is workers' safety training for accident prevention (see Section 3.1.2). Such training methods include hands-on practice, not just theoretical safety workshops. The fundamental thought behind this is that the more direct an experience is related to the lesson to be learned – e.g., a near-accident – the more it should result in a learning effect that directs an individual's behavior (Hoover, 1974). Thus, the research objective of this study was to evaluate how well VR-based safety training is applicable as an experiential learning method by providing a direct experience of potential accidents. This study's main focus was assessing the learning effects of the VR training, the user experience, and the system's usability.

6.2 Study Design

This study used a VR simulation of an indoor construction setting to investigate how VR can be applied to experiential learning scenarios regarding safety knowledge on handling power tools on construction sites. As a use case, work with angle grinders was chosen (Figure 6.1) since injuries with these power tools can have severe consequences, and several safety aspects must be followed in the safe handling of the tools. Thus, in the VE, participants were asked to make several decisions to ensure the safe use of angle grinders and pay attention to their own safety and the safety of fellow workers. For the measurement of the learning effect, a within-subjects comparison between a baseline

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[19] Contents of this chapter have been published in:

Jelonek, M., Fiala, E., Herrmann, T., Teizer, J., Embers, S., König, M., & Mathis, A. (2022). Evaluating Virtual Reality Simulations for Construction Safety Training: A User Study Exploring Learning Effects, Usability and User Experience. I-Com, 21(2), 269–281.

Fiala, E., Jelonek, M., & Herrmann, T. (2020, July). Using virtual reality simulations to encourage reflective learning in construction workers. In International Conference on Human-Computer Interaction (pp. 422-434). Cham: Springer International Publishing.

measurement (prior to the study) on safety knowledge and a post-simulation measurement was chosen.

Figure 6.1: An angle grinder with handle (on the left) and an unsafe one without handle (right).

6.2.1 Virtual Environment and Study Pre-Runs

The VE was set in an indoor construction site, including several workers as non-player characters (NPCs) and a moving forklift. An overview of the scene is given in Figure 6.2. In the VE, participants are tasked with making a cut in an air duct using an angle grinder Figure 6.1. The scene starts in the office of a foreman (also NPC) who explains the task. In order to complete the scenario successfully, participants have to make decisions regarding the work equipment and have to avoid or cope with several hazards:

1) The choice between personal protection equipment (PPE). One can choose between a helmet without and a helmet with face protection. A face shield should always be used with angle grinders, as sparks or cut parts can fly into the face. Using a helmet without face protection would lead to a re-start of the scene when cutting.
2) Choosing between two angle grinders, with or without a handle (Figure 6.1). Angle grinders should always be used with both hands, as serious accidents can occur if the cutting wheel gets stuck and the angle grinder recoils. Thus, the handle is necessary. Using the angle grinder without a handle would lead to a re-start of the scene while making the cut.
3) Selecting a safe path from the foreman’s office to the workplace. A choice must be made between walking through another worker's work area with an angle grinder and flying sparks or walking along a path where a forklift truck is moving. The path past the forklift has to be taken, as otherwise, one would have to walk through sparks and expose oneself to immediate danger. One must pay attention to the traffic and one's own safety in order not to be run over by the forklift. The

scene would re-start when one would walk through the area of the other worker or on a collision with the forklift.

4) As a last point, the own workspace has to be cleared of other workers. Otherwise, in the simulation, cut-off parts could hit colleagues. Therefore, an NPC talking on the phone must be sent away from the area. If the other worker is not sent away, he gets hit by flying parts of the bursting cutting disc from the angle grinder, and the scene would re-start.

In all cases, the foreman would repeat what the user did wrong on the re-start of the scene. A schematic overview of the virtual construction site and the placement of hazards is shown in Figure 6.2.

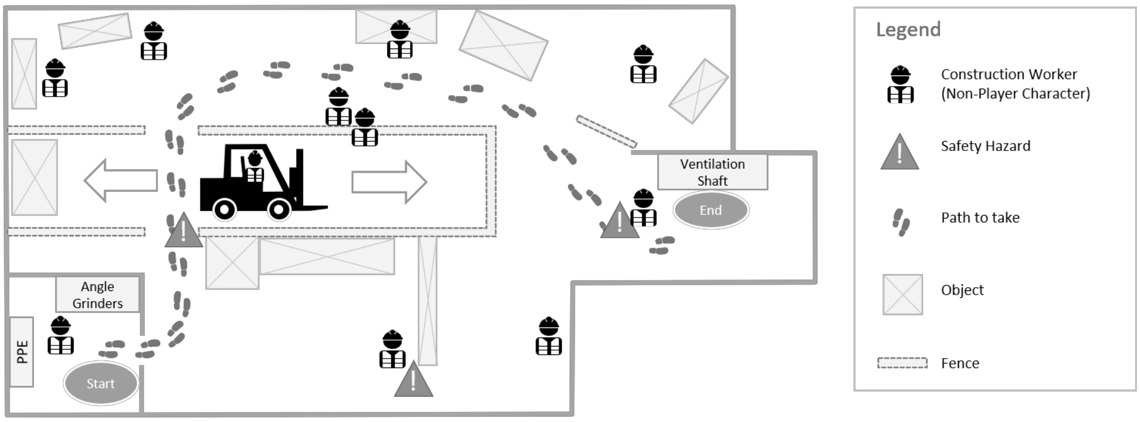

Figure 6.2: Schematic overview of the virtual construction site, the safe path participants had to take and the placement of hazards.

Before the VR training was used in the main study, five pre-runs of the study were conducted with professionals from construction research. These pre-runs were intended for quality assurance, to avoid possible inconsistencies and inaccuracies in the simulation content, and to optimize the study design.

For example, based on the experience and observations from the pre-runs, one additional hazard spot was removed from the simulation. In addition to the above-listed safety hazards, the scene previously also included a trip, slip, and fall hazard: An oil puddle was placed on the path to the ventilation shaft that had to be avoided deliberately. Walking directly into the puddle would lead to (virtually) falling and the screen would turn black before the simulation would re-start. However, this hazard was removed due to observations made in pre-runs of the study. In none of the pre-runs did any participant see or notice this puddle of oil in advance, as it was on the ground and therefore out of sight. Furthermore, it was not apparent that the puddle was meant to be a hazard. Due to the animation of falling and thus a fast visual movement of the field of view, several participants reported motion sickness symptoms in the pre-runs. Consequently, this hazard had been removed from the VR scene.

6.2.2 Participants

For the main study, 14 machine operator trainees (2 female, 12 male) participated, aged 18 to 32 years (*M* = 22.79, *SD* = 3.98). Ten participants stated that they had either some experience with VR or had at least tried it once. All study sessions have taken place in the participating training center's facility. The participants had all prior knowledge of construction site safety aspects and two years of experience as trainees.

Two participants showed signs of motion sickness during or after playing the virtual reality simulation, and their ability to concentrate was influenced negatively. Thus, their results were removed for the quantitative analysis, resulting in a final sample of $n = 12$ (*M* = 23.17, *SD* = 4.15). However, as they still participated in the interviews, we included their answers for the qualitative analysis, as their opinions could still give insights about their experience with the VR safety training.

Additionally, two training instructors, aged 32 and 61, were also interviewed after going through the same procedure as the 14 trainees to get the views and opinions of instructors towards such VR simulations. However, their results were not included in the quantitative analysis.

6.2.3 Measurements

The study aimed to examine the learning effects, usability, and user experience of such VR safety training. To investigate the learning effects, we designed a questionnaire based on the official recommendations of the German Employer's Liability Insurance Association for the Construction Industry (*BG BAU*) regarding the use of angle grinders and general construction safety aspects.

The questionnaire consisted of 36 dichotomic items, 22 items addressed general safety aspects on construction sites without any relation to the content of the simulation, whereas 14 items directly related to the VR simulation and the work with angle grinders (see Appendix L). The questionnaire was created because there was no questionnaire on the safe use of angle grinders (at least none publicly available). It was designed to investigate whether participants implicitly learn safety measures when working with angle grinders by playing the VR safety training. In addition to the 36 items in which participants had to decide whether the statements were true or false, two additional multiple-choice (MC) questions were added. The first MC-question regarded rather technical knowledge about the safe use of cutting wheels for angle grinders which was not explained in the VR simulation. The second MC-question referred to the needed personal protective equipment (PPE) when working with angle grinders, which was part of the VR simulation.

For the assessment of perceived usability, the SUS was used (Brooke, 1996) to evaluate effectiveness, efficiency, and satisfaction. The UX was assessed with the UEQ (Schrepp et al., 2017; UEQ, 2018). In addition, semi-structured interviews were conducted with participants to gain a deeper understanding of participants' insights and decision-making processes. The interviews were divided into four thematic sections:

1) the participants' background, his/her experience with VR, and pre-experience of construction work and general safety aspects,
2) the VR simulations' content,
3) the felt realism and the visualizations in the VR simulation, and
4) the built-up comprehension about the safety training and relevant safety aspects.

The interviews with the two experts were constructed in the same manner, except for adding questions that focused on other training methods used to educate trainees in the construction sector. These questions were added to establish a teacher's perspective on VR safety training for this study. Content analysis was used to analyze the qualitative material (Mayring, 2001, 2010).

6.2.4 Study Procedure

After five iterative pre-runs of the study (Section 6.2.1), the main study was conducted on two consecutive days. On the first day, participants were given a short introduction about the study without discussing the actual content of the simulation. They were handed out a demographic questionnaire and an informed consent for participation. Participants were also informed that they could withdraw from the study at any time and that their data would be deleted. Then, they completed the questionnaire with 38 items about general occupational safety on construction sites. At the end of the first day, each participant received an individual time slot for their session on the next day.

Each session on the next day started with a brief explanation of the VR headset and the controllers. Then, they were equipped with the hardware and started in a short VR tutorial. In this tutorial, participants learned how to move around in the VE, pick up objects, and use the angle grinder. After the tutorial, participants were teleported into the foreman's office on the construction site. The foreman gave them their task, and they had to choose between a helmet with or without visual protection and between two angle grinders, where one of both was missing the handle. In the foreman's office, an overview map of the scene hung on the wall, allowing participants to see their designated work area and the site's layout.

The VR simulation could only be successfully completed if all safety aspects were met. After finishing the simulation, participants removed the VR hardware and were briefly asked about their general state of health and if any motion sickness symptoms were present. Then, they went into another room together with the study facilitator and completed the 38-item questionnaire on general occupational safety again before filling out the SUS and the UEQ. Finally, the semi-structured interviews were conducted with participants.

6.3 Results

The analysis focused on three main aspects: the safety questionnaire for handling angle grinders pre- and post-VR, the perceived usability and UX of the simulation, and all statements within the qualitative interviews. As mentioned in section 6.2.2, the data of only 12 participants was included for the analysis of the questionnaires due to motion sickness symptoms that occurred during or after the VR experience. However, the interviews of all 14 participants and the two experts were included in the qualitative data analysis.

6.3.1 Safety Questionnaire

The safety questionnaire consisted of 36 dichotomic items and two MC questions. Of the 36 items, 22 items focused on general safety aspects on construction sites and 14 items focused on simulation-related safety aspects. The first MC question related to knowledge that was part of the simulations' content. The second MC question related to technical safety knowledge of angle grinders, which was not part of the simulation.

A paired sample t-test was used to calculate the differences in scores to compare answers on the safety questionnaire. The results did not show a statistically significant difference between the complete 36-item questionnaire and the 22-item subset (Table 29). However, on the 14-item subset questionnaire with simulation-specific questions, the t-test revealed a significant difference in the scores between pre-VR (M = 11.08, SD = 1.31) and post-VR (M = 12.17, SD = 1.19) measurement; $t(11)= 2.31$, p = .041, with d_{Cohen} = 0.67.

Table 29: Paired sample t-test to examine pre- and post-results of the safety questionnaire (n=12)

	Test results pre-VR		Test results post-VR		
Questionnaire	Mean	Std. D.	Mean	Std. D.	Paired t-test
Safety questionnaire (36 items)	28.17	2.69	29.00	2.49	NS
Subset on general safety (22 items)	17.17	1.99	17.33	2.06	NS
Subset on simulation specific questions (14 items)	11.08	1.31	12.17	1.19	*

Notes: T-test results: * p < 0.05, NS = no significance.

The two MC questions were analyzed separately. The first question, focusing on technical knowledge about angle grinders, asked participants which aspects must be considered when working with angle grinders (for the question and the answers, see Table 30). All three given options should be considered, although only the first two are common knowledge among construction workers. Comparing pre- and post-VR answers has shown that the number of correct answers was the same.

Table 30: Number of correct answers to the technical safety questions about working with angle grinder discs ($n = 12$).

Which of the following aspects should be considered when working with angle grinders?	Pre-VR	Post-VR
Disc must be certified for the material.	12	12
Disc must fit on the protection.	12	12
Expiration date of the disc may not be exceeded.	3	3

The second MC question asking about necessary PPE during the work with angle grinders showed differences in the scores between pre- and post-VR. The question asked which PPE one should use when working with angle grinders and, except for barrier tape, all of the listed PPE is recommended by the German Social Accident Insurance (Deutsche Gesetzliche Unfallversicherung e.V., 2017). After playing the simulation, scores were higher for helmet, safety shoes, and gloves. However, scores for breathing mask and hearing protection dropped compared to pre-VR (see Table 31).

Table 31: Correct answers for the question about needed Personal Protection Equipment (n = 12).

What kind of PPE should you wear, when working with angle grinders?	Pre-VR	Post-VR
Safety glasses/Face shield	12	12
Helmet	3	11
Breathing mask	5	2
Safety shoes	11	12
Gloves	4	8
Barrier tape	0	0
Hearing protection	12	9
No PPE is required	0	0

Note. Green highlighted = increase of correct answers; Red highlighted = decrease of correct answers.

6.3.2 Usability and User Experience

To analyze the system's usability and UX, the UEQ and the SUS results were calculated and combined with interview statements. The SUS result was 78.7 ($SD = 11.6$). According to Brooke (2013), the score is "good" on the adjective rating and "highly acceptable" on the acceptability range. A score over 68 is considered above average and indicates a positive perceived usability. Statements from participants support the results. For instance, one participant noted that the controls in the simulation were easy to understand after trying them in the tutorial scene. Besides comments about memorizing which button resulted in which action, no other problems or challenges with the controls were mentioned. Regarding the hardware, most participants felt comfortable wearing the VR headset and stated that using VR as a training method is user-friendly.

Results of the UEQ showed good to excellent ratings of the simulation. The scores for each category of the UEQ can range between -3 and +3. The UEQ scores for each scale were: attractiveness (*M* = 2.06, *SD* = .61), perspicuity (*M* = 1.88, *SD* = .93), efficiency (*M* = 1.6, *SD* = .79), dependability (*M* = 1.52, *SD* = .70), stimulation (*M* = 2.21, *SD* = .87), and novelty (*M* = 1.7, *SD* = .66). The UEQ also allows to group scales together for a *pragmatic quality* (perspicuity, efficiency, and dependability) which scored 1.67 and for a *hedonic quality* (stimulation, originality) which reached a score of 1.95. The scores for the individual scales are shown in Figure 6.3.

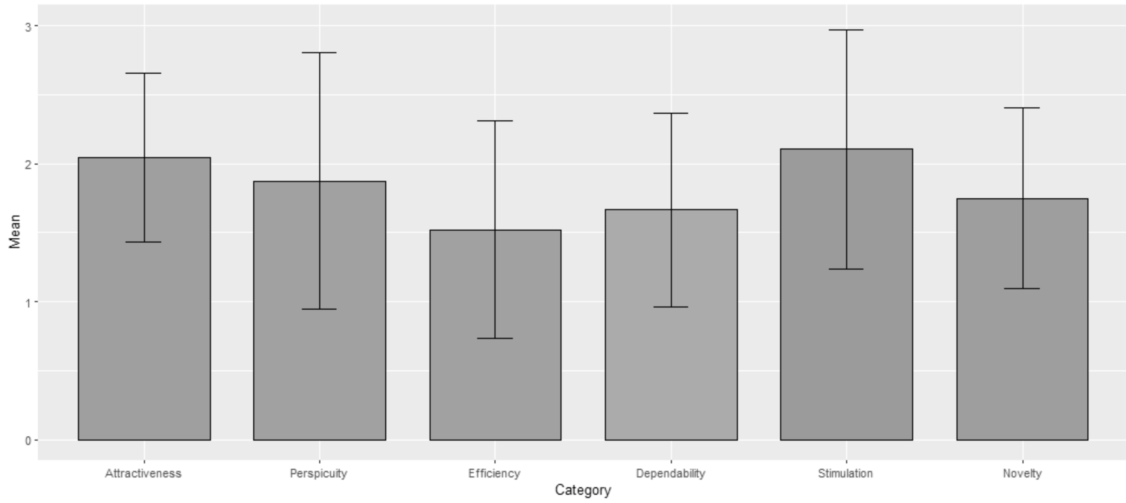

Figure 6.3: Results of the User Experience Questionnaire (UEQ) for the VR safety training

Interview statements support the UEQ scores. Most trainees stated they would prefer VR safety training over theoretical training and rated the VR simulation positively. All 14 participants rated the visualizations used in the simulation as very positive. Regarding the felt realism, 11 participants stated they found the simulation to be very realistic overall. Nine participants rated the simulation as helpful for the training of work safety aspects, especially using the correct PPE. The possibility to virtually experience work hazards was rated as highly effective. Ten participants stated that they feel more confident regarding general work safety aspects on construction sites after experiencing the simulation. Finally, all participants managed to solve the task on their own, without any interfering comments from the study facilitator.

6.3.3 Reflective Learning

During the interviews, participants mentioned several statements that referred to past experiences. They reflected on previous experiences on real construction sites based on what they had experienced in the VR simulation. Such processes refer to “Reflective Learning”, an internal process that re-evaluates former experiences and may change perspectives (Boyd & Fales, 1983; Schön, 1983). Even though reflection was not explicitly intended to be part of the evaluation, it naturally came up in the interviews.

During the analysis, three origins of reflective statements emerged:

1) simulation related,
2) related the simulations’ content to personal experience, or
3) related to personal experience beyond the simulation’s content.

An example of a reflection that was simulation related, P5 referred to a situation during the VR simulation in which he collided with the forklift: "*Generally, it was about the learning effect. No, it was about, let's say, for example, to not run past the worker, because there you are putting yourself at risk. On the construction traffic route, I reacted as I expected. He would drive back and forth […]. And that I had to cut it [work piece] there, was clear. But I didn't expect that an accident would happen. That surprised me, but also positively, because it recalls that to the mind*." (P5, pos. 43).

Then, as an example for a statement that was based on personal experience and related to the simulation content, for instance, P2 referred to existing teaching material in the trainee center and the experiences from real constructions toward the simulation: "*That has already been taught in the education center as well as in the vocational college and company-internally. It is something completely different, if you really experience it on a construction site, that's where the simulation has an essential effect, since it is closer to reality compared to sitting in class and being told, 'yes, that is to mind out there, watch this, watch that.'*" (P2, pos. 24).

Last, as an example of statements that relate to personal experience and went beyond the simulations' content, for instance, P5 mentioned *"Since I already had a bad experience with these tools [angle grinders], well I had a disc that busted while working. I was lucky though, it almost hit me […]. In that situation a helmet or safety glasses do not help. No, the point is, you should definitely use it [angle grinder] with both hands. I did not always do it. […] It is simply not always possible, you have to, cannot always use the slide arm. […] Then you are really sitting here like this, in a small corner, […] because sometimes you simply do not have space. […] These are such aspects, the theory is nice, but in practice it is always different."* (P5, pos. 79).

The statements were then analyzed for major categories and four categories emerged. Statements were related toward:

- the content of the simulation and the behavior within the simulation,
- an evaluation and improvements for the simulation,
- learning experiences and comparisons of training methods, or
- practical work experiences, work safety and attitudes.

The publication of Fiala et al. (2020) can be referred to for a more detailed description of each theme and further examples.

6.3.4 View on the Simulation and the Safety Aspects

All participants considered the content of the simulation to be reasonably realistic. As one participant concluded what he liked about the simulation: *"Actually, the overall picture. That it's structured from start to finish, like a construction site. Like in a workshop. That you have to get your tasks, take your personal protective equipment, your tools and then also look where do I have to go now, what do I have to do?*" (P9, pos. 71). In comparison, although the overall rating was positive, some have pointed out that construction sites are usually much messier, for instance: *"So first of all, [the simulation was] amazingly* *realistic actually. In terms of presentation and quality. But on the other hand, totally unrealistic, because there's a lot more going on at the construction site. And yes, that [a real construction site] would not be so tidy"* (P1, pos. 62).

Another reoccurring aspect that should be improved in the simulation was the behavior of the forklift. The forklift driver simply drove the forklift forwards and backwards, as P3 stated: *"Yes, in the real world it's always something else. Because it's not just me who really does something, but the others [workers] also interact with me. It sounds stupid now, but this simulation with the forklift is nonsense. Because when it [the forklift] is standing there and I walk by and all of a sudden, the simulation is over [because the forklift driver simply runs me over], that's just stupid."* (P3, pos. 46). One participant even mentioned having looked the forklift driver into the eyes, without any change in the driving behavior, which he thought was unrealistic.

Regarding the task inside the simulation, seven participants explicitly stated that the task and the feedback on safety aspects were clear. In general, the participants suggested to increase the complexity of the scenario inside the simulation, for instance, by adding more PPE that could or could not be necessary for the scenario. More importantly, although participants were holding VR controllers, they stated that the task was overall realistic.

In contrast to the views of the trainees, the perspective of the two experts was somewhat more heterogeneous. One of both instructors rated the simulation very positive and as an effective safety training method. He also added that he would be ready to apply such methods as additional tool in teaching. In his view, the use VR simulations could be a very efficient way to teach and experience hazardous situations and their consequences: *"So I think it [the VR simulation] makes sense that way. […] It also makes an impression. I think it's even easier for young people to remember than if someone stood in front and said, remember, remember, you have to take the helmet, you have to take that angle grinder. I think that's better [taught with such experiential simulation]*" (E2, pos. 65). Due to the direct (virtual) experience, he sees advantages above all for memory capacity in learning and gaining the consciousness for safety hazards.

However, the other, more experienced instructor was not so keen of the VR simulation. He did rate the VR simulation as very helpful in creating awareness of hazards. But he explicitly limited its use as an extension of existing teaching methods (theoretical training, on-the-job training). As he had no prior experience with VR, he found it difficult to use the controls, to understand the foreman's instructions, and to guide himself through the virtual construction site.

6.4 Discussion

In this section the results and limitations of the study will be discussed, focusing on the experiential learning through VR simulations and the application of VR safety trainings from the view of construction trainees.

6.4.1 Experiential Learning and Reflective Interviews

The study's results indicate that playing the VR simulation led to a learning effect concerning safety aspects regarding the work with angle grinders. Results of the safety questionnaire indicated that, while results for the subset of questions with relation to the simulation increased, the results for the general construction site safety stayed on a comparable level. The finding supports existing literature on the educative use of VR (Sacks et al., 2013).

In addition, results from the first MC question on rather technical knowledge regarding angle grinders suggested that (1) participants did not gain any knowledge about these aspects during the VR experience and (2) that they did not read up on that matter after they filled out the pre-VR safety questionnaire. Whereas the first aspect is rather apparent, the second aspect supports the finding that participants, in fact, gained knowledge through the VR safety training rather than through reading up on specific safety aspects when using angle grinders.

The second MC question indicated that some participants mapped the content of the VR simulation very accurately to the answers to the question. In the simulation, participants (virtually) wore gloves and had to select a helmet with a face shield. Breathing masks and hearing protection were not part of the simulation. The results suggest that if the content of the simulation is incorrect or incomplete, participants may learn the content as it is presented and thus risk learning incorrect information.

Finally, the study has shown that reflective processes were triggered in the participants through the combination of a VR simulation for experiential learning and semi-structured interviews that were conducted after the VR experience. This finding is generally supported by the literature on reflection and reflective learning with VR, as VR enables users to reflect the virtual experience with previous and future real-life experiences (J. Jiang & Ahmadpour, 2022; Stavroulia & Lanitis, 2019) and that it can be fostered with digital storytelling (D. Kim et al., 2021). Thus, VR simulations not only make it feasible to learn safety measures in the handling of power tools, but also to learn how to interpret what has happened after the simulation by talking about personal experiences. As in the case of this study, such reflective processes can be triggered by simply asking questions. However, it is also likely that an exchange with more experienced workers or safety experts can support this experiential learning method through personal experience in direct conversation.

6.4.2 VR Safety Trainings as Learning Method

An essential aspect for this thesis was that trainees from the construction industry participated in this study and could judge the VR simulation with professional background knowledge, thus increasing the external validity of results (Khorsan & Crawford, 2014). The content of the simulation was rated as reasonably realistic by all participants.

The scenario in the VR simulation was rated very positively overall and participants stated their desire for further developments of the scenario. However, the simulations’ content was rated as very limited. The choice of selectable PPE included only choosing between two helmets, the own VR representation was already wearing safety gloves, there was only a choice between two angle grinders, and the scene was always the same. Thus, the play time of participants was relatively short, affecting their overall experience, as not every participant experienced every possible hazard, leaving the possibility of not learning certain safety aspects. To minimize the repetitions (after each accident), the scenario should include more dynamics, like replacing hazards in the scene and preventing participants from anticipating hazards.

The usability and UX of the VR simulation were rated positively by trainees and experts. Trainees expressed a preference for VR as an additional learning method over theoretical training, backing the findings about dissatisfaction with existing models of training (Li et al., 2012; Wilkins, 2011). The two instructors had slightly different opinions on the VR simulation after experiencing it themselves. The younger instructor was open to using such VR simulations directly in training. In contrast, the older instructor explicitly pointed out that he would only use them as an additional method to the existing ones.

6.4.3 Limitations

One limitation is the final sample with data from 12 participants. Although the sample size is comparable to other studies in the same area of research (e.g., Caine, 2016), the sample is not large enough to be representative. Thus, the results on the learning effects should be treated with caution, and further research on the field of VR-based experiential learning should be carried out. However, the sample was recruited from the target group for such VR simulations, thus making their statements towards such simulation as a training method highly valuable.

Another limiting aspect is that the VR simulation was tested independently and not in comparison to conventional teaching material. For instance, such comparisons between VR and existing teaching material could demonstrate differences in trainee motivation or knowledge acquisition. However, this study demonstrated that the simulation increased participants' awareness, hence the efficiency of learning, backing the former findings of Sacks et al. (2013).

Finally, it should be considered that the novelty effect might have influenced participants’ statements on the VR simulation. In total, four participants stated that they had no prior experience with VR, while ten participants had tried VR at least once before the study. Thus, their assessment might have been influenced positively by the possibility of trying out VR. However, all participants had prior experience with digital building simulations, as the trainee center used stationary construction machine simulators. Those construction machine simulators consisted of a seat, steering wheel, gearshift, and buttons of construction machines, trying to replicate real construction machines. Thus, although participants have not used VR extensively, they all had experiences with digitally supported teaching methods.

6.5 Summary

This chapter has presented a study of a VR safety training on safety aspects when working with angle grinders. Results have shown that the safety training led to short-term learning effects for users and that the training is a valuable alternative to other training methods. Participants had prior experience with simulation-based learning methods and rated the VR approach very positively. However, results on a safety questionnaire have revealed that participants did map inconsistencies in the VR simulation accurately on the knowledge test. In other words, due to missing safety aspects in the VR simulation, participants thought they were not necessary. Finally, discussing the VR scenes and accidents in the interview triggered reflective processes in the participants and comparing the VR experience to real-life experiences.

7 Safety Aspects of Virtual Reality

This chapter[20] aims to analyze VR-related accidents and how they can be prevented. While the previous studies concerned studying safety-related aspects *in* VR (Chapters 5 and 6), here, the safe testing *with* VR hardware is focused. This chapter provides an overview of occurring accident types and their root causes. Finally, it discusses their relevance for the design and operation of VR Labs.

Figure 7.1: VR use in laboratory vs. domestic settings

7.1 Research Objectives and Problem Statement

As presented in Section 2.3.1.3, accidents in handling VR hardware are accumulating. Although the premises between VR use in laboratory settings and domestic use are different (Figure 7.1), such analysis could still point out relevant safety aspects that must be considered when using VR for research purposes. The occurrence of VR-related accidents and injuries is a relevant challenge for HCI because the technology visually (and auditorily) isolates the user from their contextual environment while using VR. VR-related injuries can be severe enough to have life-altering traumatic effects on users' lives (e.g., Jones-Dellaportas et al., 2022; Warner & Teo, 2021).

Since VR-relating accidents are usually not observable by researchers, a similar approach will be taken for this purpose, as already presented by Dao et al. (2021) using social media data. On the online platform *Reddit*, a community (a so-called *subreddit*, or short: *sub*)

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[20] Contents of this chapter have been published in:

Jelonek, M. (2023). VRtoER: When Virtual Reality leads to Accidents. A Community on Reddit as Lens to Insights about VR Safety. *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, 1–6.

has formed around the topic of sharing videos, photographs, stories, and *Memes*[21] about VR-related accidents and injuries called *r/VRtoER*[22]. Among others, the community comprises VR enthusiasts, VR experts, VR users, and enjoyers of fail videos.

"VRtoER" stands as the acronym for "[From] Virtual Reality to [the] Emergency Room". The community's name is not meant literally from VR to ER but as an exaggeration for VR-related accidents. In the description of the community, it refers to sharing "VR injury only". The sub was created as a follow-up after the user *u/uncommonpanda* replied solely the text *"r/VRtoER"* on the comment "*Will be exchanging that VR headset for an ER neck brace*" in the subreddit *r/gaming* on a VR fail video[23]. In this video, a woman runs into a brick wall/chimney while using a VR headset. Comments on Reddit that consist solely of a name of an existing or non-existing subreddit are supposed to show fellow users under which subreddit the submission would (also) fit well.

The content of r/VRtoER can primarily be defined as "accidents or injuries that resulted through or with the use of VR headsets". With the content in r/VRtoER, the community might contribute to understanding accident patterns in the (domestic) use of VR systems. For this, 200 submissions of the subreddit have been analyzed to understand:

1) the incidents of accidents, by trying to understand what happened and how it happened,
2) the cause of accidents (why the accident happened), by trying to understand the reason for the incident, and
3) how such an accident could have been prevented.

Much content in the subreddit is followed by a discussion about whether the submitted content had an existing right in the subreddit. Such discussions define the community's purpose and the shared focus more precisely. For instance, under the submission of a video in which a player kicks slightly an open drawer in front of him (ID 185), users disagreed with the submission, as it would not show "an accident". However, the submission's author clarified: "*This sub is for posting accidents that happen when a person is in VR like hitting stuff when you're in VR. Not just cases where the person has to go to the hospital. And there was a small accident he if you didn't notice. He hit stuff when if VR unaware of the surroundings in a very stupid way and that is what this sub is about.*"[24].

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[21] A meme is defined as "an amusing or interesting item (such as a captioned picture or video) or genre of items that is spread widely online especially through social media" (Merriam-Webster, n.d.)

[22] www.reddit.com/r/VRtoER

[23] https://web.archive.org/web/20230624102526/https%3A%2F%2Fnp.reddit.com%2Fr%2Fgaming%2Fcomments %2Fae6j7q%2Fgrenade%2F

[24] https://web.archive.org/web/20230624124948/https://old.reddit.com/r/VRtoER/comments/j16lnb/video_my_dad_ playing_superhot_on_psvr_for_the/

Less dangerous accidents are also regularly picked up in the subreddit via memes or other meta-content. For instance, one submission[25] showed an abstractly drawn meme in which a player plays in a 1.2 x 1.2-meter apartment. The player gets scared heavily and hurts his hand. This meme indicates satirically that:

1) in many submissions the use of VR systems occurs in play spaces that are too small,
2) users react impulsive and excessively while playing (e.g., getting scared and running in the opposite direction), and
3) a vast number of submissions showing minor hand injuries.

7.2 Procedure and Data Filtering

A script using the *Python Reddit API Wrapper (PRAW)*[26] as well as *RedDownloader*[27] packages to scrape the data of r/VRtoER was implemented to generate the data set. Then, the media and the comments from 200 of the most upvoted posts (or 'submissions') since the beginning of the subreddit were downloaded. For each post, many different parameters were extracted. The most relevant parameters beyond media files and comments were the submission text, title, score (upvotes), number of comments, and submission date.

The process for filtering the data is shown in Figure 7.2. The data set was first scanned for duplicates, deleted submission files that could not be retrieved otherwise, and meta-content like memes about the community or ads. In this first step, 42 data entries were removed (21%). Then, in a second step, the media files were scanned to gather further context information like the general happening (for videos) or if further information was provided (for photographs and videos). Submissions showing only images of injuries or hit objects were removed when no further or too little information about the incident was provided. For instance, image submissions showing bloody fingers or punched computer monitors were excluded from the analysis when the submission authors gave no further explanations of the incident. As this was the case for the majority of image submissions, due to this exclusion criteria, the document set was reduced to 94 data entries (47% of the original data set). Further information about the happening was documented for each data entry during this filtering step. If the contextual information of the submissions allowed it, additional information was documented, like which object was hit, the used game/app, the used VR device, the locomotion technique, what was recorded (for videos), or if spectators were present. In addition, the first inductive categories were created describing the accident incidents.

[25] https://web.archive.org/web/20230707114946/https://old.reddit.com/r/VRtoER/comments/mlgqfw/this_sub_in_a_nutshell/

[26] PRAW: The Python Reddit API Wrapper, https://praw.readthedocs.io/en/stable

[27] RedDownloader 4.2.0, https://github.com/JackhammerYT/RedDownloader

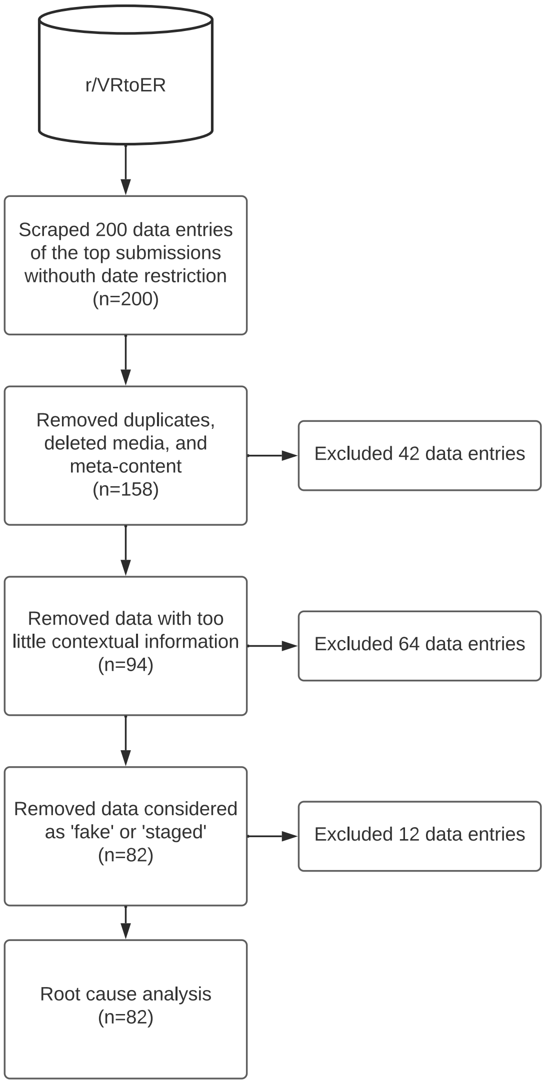

Figure 7.2 Data gathering and filtering process

Then, in a third scan, the videos were also rated for their plausibility and if they were 'fake' or not. For the fake assessments, the comments beneath the videos were scanned, especially when the videos showed somehow suspicious incidents (e.g., misuse of hardware). In total, twelve data entries were removed. Five videos were rated as fake or staged, and for seven videos a rating was not possible due to missing contextual information. Thus, with this strict filtering process, the final data set was reduced to 82 entries (41% of the original data set) and contained submissions between May 2019 and October 2022.

The data set was then further checked for contextual information. Repetitive themes and categories were noted. Specifically, it was documented:

1) what happened during the incident (relevant sequence of events),
2) which actions led to it (how the incident happened), and
3) what was the cause of the incident, i.e., why the accident happened.

Based on this qualitative process, more general categories were defined for the incidents and the accident causes.

7.3 Results

82 videos and photographs were rated as non-fake and gave enough contextual information to analyze the incident (see Appendix L). Regarding the incident categories, in 25 cases (30.5%), the player fell over, whereas in six cases (7.3% of total), the player fell *head-first* into a wall or another object. Other categories were running into objects or a wall (22%), hitting the head on furniture (9.8%), hitting another human being (9.8%), hitting objects above or in front (14.6%), jumping into objects or a wall (4.86%), or other cases.

Regarding the different objects that the player collided with, or they hit with the controllers, the objects that had the most impact on the accident were singled out during the analysis (Table 32). In most cases, the players hit some furniture (e.g., chairs, tables, TV), fell on the floor, or collided with room boundaries (e.g., walls, column pillars). In two cases, no object was hit, but the VR space was invaded. In the first case, a *near miss* could be observed as the VR player almost hit a child, and in the other case, a cat bit the VR player in the foot.

Table 32: Type of objects the users collided with

Category	Incidents	Percentage
Furniture	30	37%
Floor	19	23%
Room Boundaries (e.g., Walls)	16	20%
Ceiling (e.g., lamp, fan)	5	6%
Another Human	5	6%
Unknown	3	4%
PC	2	2%
None	2	2%

In trying to understand the root cause of the accident, six main categories were identified (Figure 7.3). Most accidents could be understood as due to immersion, referring to situations in which players got scared and made excessive movements or situations in which they seemed to have forgotten their presence in their real environment. In 22 cases, the room space was not suitable for the VR experience. In 16 cases, sensory-motor problems (e.g., losing balance) seemed to have caused the accident, followed by an invasion of VR space, spectator engagement, or hardware not adequately used. In one case, the cause could not be understood. In the following subsections, the categories will be discussed. In addition, the cases of child endangerment through VR use will be explained before discussing the relevance of the results for VR laboratories.

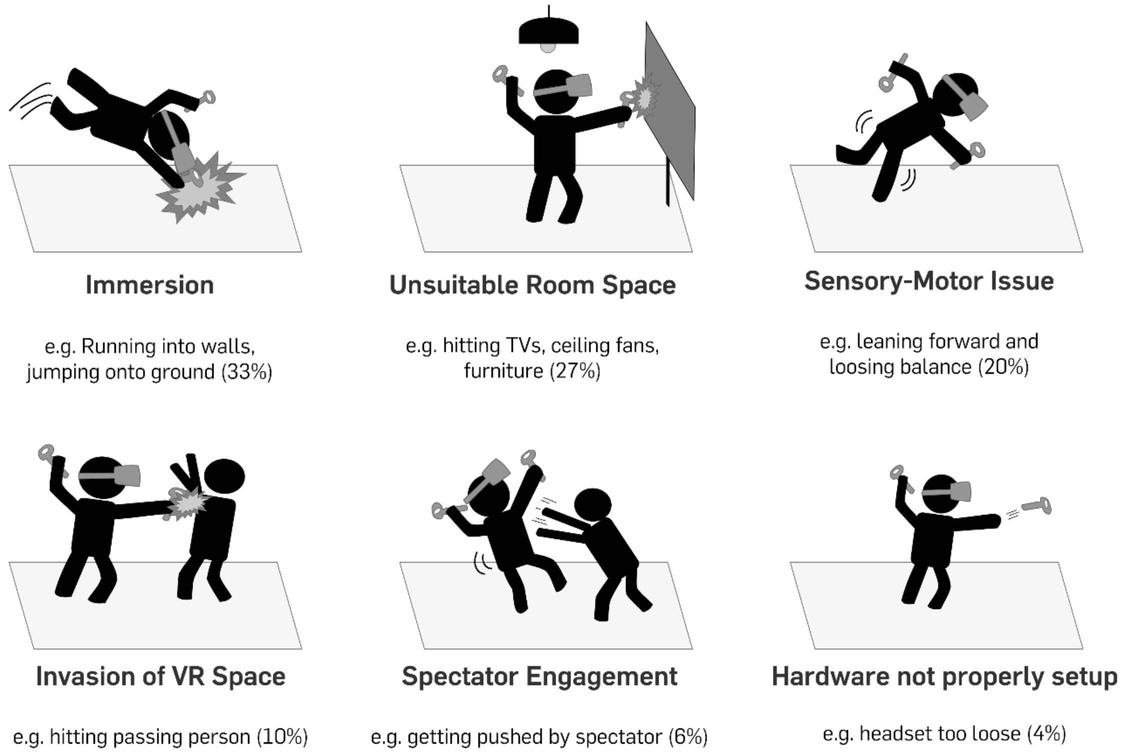

Figure 7.3: Six categories of VR accidents

7.3.1 Immersion

This category was used as an umbrella term for incidents in which players seemed to have forgotten their presence in or the boundaries of the real room because they were immersed in the virtual world. For instance, in at least five cases, the players got scared from what they experienced in VR (e.g., Zombie appearance, fast oncoming bus) and had a flight reaction. In all these cases, the players started running into the wall or other objects. Besides these flight reactions, in two cases, the players tried to lean on a virtual table, causing them to lose their balance and fall forward on the ground.

Twelve accidents involved jumps during a VR experience called "*Richie's Plank Experience*". In this VR experience, players are walking on a plank at the edge of the top of a skyscraper. In many of these cases, this VR experience has led players to decide to "jump down". However, instead of flying harmlessly toward the ground in the virtual world, as players seem to expect in these moments, they make a physical jump in their real environment, causing them to hit their head on the floor, jump into the TV, a Christmas tree, or other objects. These videos repeatedly lead to discussions in the subreddit, questioning the decisions and actions of players or accusing these videos of being fake, as one user described: "*I cannot comprehend how this man just decided to L E A P*" (ID 1).

7.3.2 Room Space

The second category refers to room spaces unsuitable for VR interaction. In five cases, players hit an object on the ceiling (e.g., a lamp, fan, light bulb). Even if safety mechanisms such as VR play area boundaries are used, they usually have their anchor points on the ground to prevent tripping or colliding with objects. In six cases the players hit an object or a human in front of them because of a VR space that was too small. In another six cases, the players ran into objects like the TV or other furniture. These cases suggest that no boundary system like *Guardian/Chaperone* was used, as these systems could prevent running into the TV by switching to the see-through mode as soon as the player hit the *Guardian* border. The case of running into and breaking the TV reoccurred so often in the community that a user commented on one of the videos: "*Sometimes I think the whole VR gaming industry is a front by the TV companies to drive more sales*" (ID 41).

Figure 7.4: Configuration of the VR play area with Meta's Guardian system (left) and the visual warning when movements go beyond the defined area (right).

7.3.3 Sensory-Motor Issue

The category 'sensory-motor issue' refers to accidents in which the missing visual feedback from their real environment led users to do movements that caused an accident, for instance, by leaning over too far, losing balance, or hitting themselves. In total, 16 videos fell into this category. In 14 videos the VR user lost the balance. Here, two types of actions could be identified. Losing balance was either the result of the in-game locomotion/interaction within the VE or because the users leaned too far in one direction to reach certain objects. Examples of the first accident type are, for instance, two videos where VR users lost their balance while playing a skiing game and leaned too far to one side before losing balance. In another example, the VR user wanted to climb over a virtual object, seemed to expect an earlier resistance during the step, lost his balance and fell forward. However, this is a borderline case in which it is not entirely clear whether the root cause was the immersion or a disturbance of the sensory-motor system. For the second type, users leaned too far forward in the videos and possibly expected some physical resistance of virtual objects but ultimately lost their balance. For instance, in one case, the VR user tried to look into a car, leaned forward, and fell (ID 140).

7.3.4 Invasion of VR Space

The data set revealed seven accidents and one near miss as invasions of the VR space. In such cases, people (or animals) walk into the VR play area of the player and put themselves in danger, since the player, depending on the level of immersion and sensory impressions, does not notice the intrusion. with the controller. In five cases, the player started hitting something fast (e.g., during a boxing game), and in three cases the intruding person was hit in the head with the controller.

7.3.5 Spectator Engagement

While there were spectators present in most of the videos, five cases were identified in which the spectator engagement was probably the cause for an accident, in all cases during the ‘plank experience’. In three of these cases, the VR players were pushed by one of the spectators, leading to accidents. In one case, the player lost balance through the push and fell head-first into a wall. In the other two cases, spectator engagement probably led to a misunderstanding in their communication. In the first case, an older woman is doing the plank experience and the spectator repeats “*step to the right. you’ll just float, you’ll float*” which causes her to leap forward, against the wall (ID 24). In the second case, a young child asks the people around him “*can I just run and jump off?*”. After receiving a “*yeah*” as an answer the child starts running straight into the TV, while the spectators still tried to stop him (ID 28).

7.3.6 Hardware Setup

In total, there were three cases in the data set where accidents with the hardware occurred. In two cases, the users did not use the safety standards of VR hardware correctly: in one case, the headset fell off a user's head because it was not tightened correctly on the head, and in the other case, the user did not use the safety straps on the controllers and a controller slipped out of his hand. In the third video, a participant was sitting on a movable chair (for multimodal support of the VR experience). However, it was not adequately anchored to the floor and fell over with the participant.

7.4 Discussion

In this section, the accident categories are discussed for the case of VR Labs. As the data set in this study was scraped from social media data and concerning VR use in domestic settings, there are limitations to generalizing the results.

7.4.1 Preventing VR-related Accidents

Based on the results, two accident categories can be ruled out in advance for VR Labs: "Invasion of VR space" and "Spectator Engagement". The first category may still occur when a study facilitator needs to set up the hardware and temporarily invade the VR space of users. Here, verbal communication with the participants should prevent accidents, e.g., if the participant would accidentally hit the study facilitator. Then, as an additional safety mechanism, methods should be used to integrate passersby spotting into the headsets (McGill et al., 2015; von Willich et al., 2019). However, such a scenario is more realistic in multi-user settings where users play VR in the same room. The category "Spectator Engagement" should be negligible as study facilitators should not disturb or negatively impact participants' VR experience.

The categories "Hardware setup" and "Room Space" concern a proper and approved setup of the VR Lab. Both accident categories can be avoided with relatively low effort. With play area boundaries in VR, participants should stay far away from surrounding objects or walls. Controllers should be attached to users' wrists via leashes, and headsets should be appropriately placed and secured. Ideally, a specially prepared testing room as a "VR Lab" provides a sufficient VR play area.

More challenging is the design of appropriate VR experiences for the categories "Sensory-Motor Issues" and "Immersion". In the case of sensory-motor issues, an attempt must be made to build VR worlds in a way that participants do not get the idea of leaning over objects to reach them or get a better view. An example here can be barrier railings on heights. Participants should be able to look over the railings without having to lean forward to get a better view of the surroundings. The same applies to objects that need to be reached. Such objects should be accessible and not located on spots to which participants may have to lean over. The category “Immersion” is difficult to evade, as one of the goals should be to enable a high degree of immersion. However, VR scenes should be designed in a way that participants do not generate excessive reactions, such as getting scared and starting to run physically.

7.4.2 Child Endangerment

During the analysis, several VR-related accidents of children were found. In (at least) six cases, children were endangered using VR, either by using VR despite being too young or because they got hit by others (9 cases in total, but due to missing demographic information in at least six, it was a young child).

Only in one of the cases no accident occurred (near miss). In four cases, children were hit by accident by an adolescent or another child due to the invasion of the VR space. In the last case, a child jumped during the VR experience and fell down head-first. In two cases, it can be seen that the children are clearly younger than 13 years, and therefore it is to be questioned if they should use these devices at all.

To avoid such cases, both the manufacturers of the devices and the parents are asked to intervene. On the producer side, even better tracking of VR space invasion could be used with stronger consequences, like a faster switch to pass-through mode. Also, better education about VR use in homes with children seems necessary. Parents should ensure that the VR play area is not accessible to children to protect them from any harm.

7.4.3 Limitations

Although strict parameters were applied about which videos to include in the analysis and videos that were even slightly suspicious were removed, there is a residual probability that some of the analyzed videos might have shown faked content. To detect and exclude fake videos, the plausibility of the video sequences was evaluated, and eventual explanations by the submitters of the content were included in the assessments. In addition, the comments under each suspected submission were evaluated. With the used approach, twelve data entries were excluded that showed misuse of VR hardware on purpose or where it remained unclear if the videos were faked or not.

Another limitation lies in the videos themselves. Although videos provide a lens on the actual context of use and the happenings of VR-related accidents, they usually do not show the accident's aftermath or explain the injuries resulting from the incidents. Also, the data set was limited to the 200 most upvoted submissions of all time, thus adding a bias to the data set toward more shocking, funny, or discussion-worthy submissions. In addition, using the most upvoted submissions, many duplicates had to be removed from the data set.

The cases analyzed could, in principle, also occur in VR Labs. However, there is another limitation of the data due to its focus. Although the data allow insight into typical accident types with VR hardware, there is this insight into domestic applications of VR. Here, specific VR Labs and domestic environments differ significantly in furniture layout (Figure 7.1).

Another limitation is that only one person conducted the qualitative analysis. In assessing the content and meaning of data, qualitative analyses can benefit from the discussions of multiple researchers during the analysis process (e.g., O'Connor & Joffe, 2020). However, when analyzing the content of the videos, the comments of other users below the submission were also included in the thought process whenever it seemed appropriate or necessary.

Lastly, the videos have shown the use of common VR hardware. Wearables, such as the vibrotactile belt presented in this thesis, were not used in the videos. Accordingly, no statement can be made based on the data set as to whether special precautions must be taken when using external wearables apart from securely attaching them to the user.

7.4.4 Summary

This study presented a data analysis on social media data for VR accidents. The data was scraped from a community that shares VR-related accidents and injuries. Due to a rigorous data filtering process, only 82 of 200 downloaded data entries were included in the analysis. The results have revealed six major categories for VR-related accidents, whereas an additional category was created, depicting accidents that included children. In the discussion, it is pointed out that only four of the categories are relevant to the design of VR Labs.

8 Design of Virtual Reality Laboratories

This chapter discusses the feasibility of VR Labs based on the experiences made in the studies presented in this thesis. Their use and purposes are outlined before design recommendations are summarized. Then ethical and privacy aspects of VR evaluations are briefly considered before VR Labs are reviewed from a socio-technical perspective. Last, an evolutionary outlook of VR Labs is presented.

8.1 VR Labs as Multi-Purpose Laboratories

The study results presented in Chapter 5 has revealed several aspects when using VR Labs as a method to evaluate vibrotactile warnings. The extent to which vibrotactile wearables can be integrated into VR environments, how various signal parameters can be adjusted and tested were demonstrated. In Section 4.2, it was also outlined which approach needs to be taken to create comparative studies between VR and real (field) tests and how these can be implemented. Such an evaluation setting, which consists mainly of VR hardware and other wearables, allows to investigate of many parameters of interest: The influence of graphical representation, the impact on dynamics and complexity in the environment, task complexity, locomotion methods, to name just a few.

Using VR Labs allows for evaluating technical prototypes in simulated scenarios that may occur infrequently in reality but have severe consequences when they do. With such VR Labs, prototypes, and solutions can be evaluated in and with VR before returning to the contextual field of use. This evaluation step can be used to generate knowledge for the design process in two ways:

1) To uncover new requirements for the prototype based on the evaluation results gained with the VR evaluation in the virtual context, and
2) To prepare a field-testing of the prototype based on the knowledge gained within the VR evaluation.

To generalize the experiences: VR Labs, as presented in this thesis, can be used in a wide range of potential use cases across various fields. With the possibility to implement a wide range of scenarios, there is no limit to the applicability of a VR Lab. Still, it must always be weighed against other evaluation and testing methods depending on resources. For instance, VR allows one to experience immersive VEs, but this immersion may only be necessary for some scenarios, and alternative test methods might be more cost-efficient.

Thus, analyzing and justifying its use for potential purposes is essential before using VR. In the context of this thesis, the justification was that testing in hazardous work environments could only be done at great expense. Due to the immersion of the VR headsets, it was possible to simulate such a working environment and to implement it close to reality.

Based on the experiences made, several possible applications are listed that emerged throughout this thesis:

- **Hypothesis Testing, Developing and Theoretical Contributions**
  In general, VR laboratories allow for the simulation of scientific experiments, allowing researchers to manipulate variables, observe outcomes, and gather behavioral data. This approach can be used for hypothesis testing and observational studies.

- **Training and Education**
  VR Labs can provide immersive and interactive educational experiences to explore complex concepts, practice skills in a controlled and safe environment, or conduct virtual experiments (Chapter 6). For instance, the observed accident outlined in Section 5.9.4.2 motivates the idea that users might need training to successfully use such devices as vibrotactile warning systems. Fostering engagement, such virtual experiences can increase the motivation of learners.

- **Individual Configuration and Personalization of Warnings**
  With VR Labs, hardware prototypes such as vibrotactile wearables can be evaluated personalized. For example, individual perceptions of vibrotactile warnings might differ. Thus, a customized configuration of vibrotactile warning patterns could be applied to overcome these individual perceptions.

- **Evaluation of Vibrotactile Parameters**
  Using vibrotactile warnings in their (virtual) context allowed to evaluate which vibrotactile parameters provide a more effective detection than others. For example, findings can allow pre-filter best parameter settings (like body location, duration, repetition, etc.) before final vibrotactile patterns are applied in a real test environment (e.g., Section 5.9).

- **Usability and User Experience Testing for Hardware and Software Designs**
  VR Labs support user-centered design processes by allowing their use in virtual scenarios before testing them in the real context. In this thesis, a vibrotactile belt was implemented and applied in a first study with users (Section 4.2). Based on the results, the comments, and the suggestions of users, the belt was then redesigned for further studies (Sections 4.3; 5.9).

- **Evaluating and Comparing Warning Systems**
  With VR laboratories, hardware prototypes can also be evaluated regarding their effectiveness for their contextual purpose. For instance, as a further study, it could

be evaluated how vibrotactile warnings compare to other systems, e.g., visual or audio warnings, or the application of electrical muscle stimulation. Based on the findings, it is then possible to consider what approach should be pursued further.

8.2 Design Recommendations

The following subsections summarize the observations and results to provide design recommendations for VR Labs that emerged throughout this thesis. Here, the recommendations are not meant as mandatory rules to be repeated but rather as design principles that should be considered when planning, modeling, and implementing VR Labs to evaluate vibrotactile wearables.

8.2.1 Contextual Factors in the Virtual Environment

In Table 33, the contextual requirements from Section 3.1 are listed, referring to sections relevant to the implementation of each requirement and sections that describe related solutions and their results.

Several key factors emerged as contributing to a successful VR experience. In general, the positive experiences were mainly due to the use of high-performance VR hardware, which is comfortable to wear and isolates users from the real environment well. Other factors were using 3D assets that generally depicted the desired environment realistically, some details that enhanced the user experience, and an appropriate soundscape.

Regarding the hazard types and categories (REQ VE 1-3, 12, 13, 15), mainly two studies were used to investigate the relevance of the requirements. In the study on proximity warnings (Chapter 5), several hazard types were implemented to evaluate vibrotactile warnings. As a recommendation, participants' knowledge has to be incorporated for such settings or should be briefed before the study when domain knowledge is required. For instance, in the study, participants partly ignored missing or defective fall protection and did not recognize it as a hazard.

In the VR safety training (Chapter 6), it became apparent that it must be ensured that the content of the VR simulations corresponds 1:1 to existing regulations and recommendations for safety measures and that the correct safety measures are implemented for each hazard. This finding was based on participants' answers on necessary PPE for the work with angle grinders. PPE that was not shown in the simulation was, after the VR experience, by many participants considered as not necessary.

Table 33: Contextual Design Requirements for the Virtual Environment

ID	Requirement:	Implementation	Results
REQ VE 1	In the virtual construction site, many hazard locations should be integrated	5.3.3; 6.2.1	5.9.4; 6.3
REQ VE 2	The VE should integrate the different accident categories and hazards	5.3.3; 6.2.1	5.9.4; 6.3
REQ VE 3	The VE should integrate proximal factors of accident causation	5.3.3; 6.2.1	5.9.4; 6.3
REQ VE 4	(Visual) distractions should be incorporated into the VE	5.3.3.6; 5.3.1	5.9.9
REQ VE 5	The VE should reproduce the noisy environment of construction sites	4.2.1.3; 4.3.1.2; 5.3.1; 6.2.1	4.2.3.4; 5.9.7; 5.9.8
REQ VE 6	The construction site should appear (visually) cluttered to resemble real construction sites	4.2.1.3; 4.3.1.2; 5.3.1; 6.2.1	4.2.3.4; 5.9.7; 5.9.8
REQ VE 7	The VE should integrate the dynamic and rapid changes in construction sites	(partly) 5.3.2	5.9.7
REQ VE 8	The tasks on the virtual construction sites should be based on the 'full-body' activities	(partly) 4.3.1.2; 6.2.1	4.3.3.3; 6.3
REQ VE 9	Hazards from the surrounding environment of the construction site should be incorporated	(partly) 5.3	5.9.9
REQ VE 10	Other trades and workers should be included.	(partly) 5.3.1; 6.2.1	5.9.7; 6.3
REQ VE 11	The activities in the virtual construction site should be cognitively demanding	4.2.1; 4.3.1; 5.3.2	4.2.3; 4.3.3; 5.9.1; 5.9.1; 6.3
REQ VE 12	In the VE several personal protective equipment should be implemented	(partly) 5.3.1; 6.2.1	5.9.9; 6.3
REQ VE 13	Situational hazards should be integrated	5.3.3.1	5.9.4
REQ VE 14	The warnings in the VE should capture attention and can be interpreted correctly	5.3.1	5.9.1; 5.9.1
REQ VE 15	Hazards that were observed in the field should be integrated into the VE	5.3.3	5.9.4
REQ VE 16	The use case of proximity warning systems should be implemented and evaluated	5.3	5.9
REQ VE 17	Several detection ranges of PWS should be implemented to reflect the different PWS approaches	-	-

Regarding visual and auditive representation (REQ VE 4-7), VEs should resemble contextual work environment, not in detail but in a plausibly realistic manner. Here, the perceived UX and realism can be enhanced by adding environmental details. For example, adding airplanes in the sky were very well received by the participants when they noticed them (Section 5.9.9) as it gave a more natural feel to the whole scenario.

Regarding the audio design, it is recommended to use realistic audio that resembles the contextual environment and increases immersion. Depending on the resources, designing the audio scape around the (visual) scenario may be reasonable. However, in this thesis, a pragmatic approach was chosen for the audio design (Section 5.3.1). Based on a freely available existing construction site recording, the sequences of events in the VE were mapped to the audio. This approach may be useful for projects that do not require a sophisticated audio design and where the environmental soundscape serves only to provide a general sense of presence (Section 5.3 and Section 5.9.8).

In general, modeling the VE can be limited only to the relevant part of the scenario. The VE can visually suggest that a broad and open environment exists, which participants cannot enter. The results of the studies showed that many participants focused only on the VR environment in the immediate vicinity and on the one relevant to completing the task. In the study on proximity warnings (Chapter 5), only two users took the time to explore the surroundings. All other participants were so focused on the tasks that they refrained from exploring the VE.

Regarding the activities and tasks in the VEs (REQ VE 8, 10, 11), it should be generally recommended to use tasks in the VE that incorporate the VR-specific interaction capabilities and challenges. Tasks in VR do not have to resemble realistic tasks perfectly, but a pragmatic approach regarding their implementation should be preferred. For instance, in Chapter 5, the task of collecting objects was a compromise between the actual research question (evaluating vibrotactile hazard warnings), the potential overload of participants in terms of VR control (response to warning as well as interaction with the VE), and generating environmental factors that allowed to explore the research question (using continuous movement in VR to encounter hazards). With this approach, the participants rated this task as not entirely realistic but understood it as a means to an end (Section 5.9.5). Also, the cognitive demands of tasks should be considered when designing VR scenarios. In order to provide an overall more reliable test, care must be taken to ensure that the cognitive load in the whole setting is also due to the task and not overly complex interaction controls with the VR hardware (Section 4.3.3).

Regarding REQ VE 14, often reoccurring hazards were critically noted by some participants (Section 5.9.8). The tested scenarios were data-driven, generating many hazards and near-misses and collecting reaction data accordingly. As a design recommendation, the VE should use as many hazards as necessary but as few as possible to examine the full impact of hazards to retain a particular surprise element of hazards and to avoid any anticipation of the hazards. With data-driven approaches, participants learn to anticipate warning signals (Section 5.9.4). In such cases, dynamic changes to the VE should be implemented (REQ VE 7). For instance, moving hazards from places that are encountered repeatedly to other spots inside the VE or generating new static hazards in the meantime that were not encountered before.

Lastly, social aspects should be incorporated to enhance realism (REQ VE 4 and 10). For instance, communication exchanges like talking on a telephone (inside the VR simulation) can add an additional layer of complexity by dividing attention toward the phone, thus mimicking real-life scenarios where attention is divided between a conversation and the happenings in the surrounding environment.

8.2.2 Vibrotactile Warnings and Wearables

The major part of the thesis has been concerned with using vibrotactile stimuli as warnings and using vibrotactile wearable for this purpose. The requirements for the wearables, the necessary sections for the implementation, and relevant results are listed in Table 34.

Regarding the wearability of the vibrotactile belt, REQ VIB 2-4 are relevant. On the one hand, the aim is for the vibration motors to fit comfortably around the body, but on the other hand, they should not appear too tight. It should be noted that for direction indicating vibrotactile warnings (REQ VIB 1), not only must the belt be able to be adjusted in its circumference, but also, if necessary, the position of the vibration motors. Using an abdominal or waist belt ensured that the wearable was perceived as unobtrusive and not interfering with movement patterns and allowed directional warnings.

The prototype featured vibration configurations that allowed the application of warnings for cardinal directions (REQ VIB 1). Additionally, warnings for objects above were displayed with the vibration of all motors. However, when multiple hazard spots were nearby, the warning signals could not be resolved by participants, as too many signals were given in a short time, thus, were confusing to participants (REQ VIB 5). In addition, according to participants, warnings from above were perceived as particularly distinct (Section 5.9.1). Future vibrotactile designs could evaluate two-level warnings, for instance, starting all vibration motors at once to get the worker's attention and, after a short pause, only vibrating in the direction of the hazard. However, such a design must first be tested for perceived complexity (REQ VIB 7). The vibrotactile signals used in the thesis were deliberately kept simple (and binary) so that participants were aware of a hazard nearby when they felt a vibration (REQ VIB 5 and 7).

The design recommendations for the warning parameters refer to the adjustability of parameters and the detection of vibrotactile warnings. First, to use different warning directions, an interface must allow vibration motors to be addressed individually (or at least by body area). When using microcontrollers to design custom wearables, the wearables should offer appropriate interfaces to forward the signals to the vibration motors (REQ VIB 1, 6, and 10), minimizing the microcontrollers' logic and remaining flexible in setting all parameters.

The flexibility in configuring vibrations and the wearable's autarkic functioning allowed testing the vibrotactile wearable within VR and in a real environment, where the commands were sent to the microcontroller by a mobile phone. Thus, this approach allowed for mobile testing (REQ VIB 8), which may be relevant for comparative studies between VR and real environments. In this regard, the requirements REQ VIB 8-11 refer to mobile testing of vibrotactile wearables. The general recommendation is that no complex logic should be implemented on the microcontroller. Instead, external devices (handheld, stationary) should communicate relevant warning messages toward the wearable and implement all logic needed for logging, monitoring, or configuring warning messages.

Finally, as a recommendation for evaluation settings, a function should be implemented that allows all vibrations to be tested with participants before an actual study session starts. On the one hand, this will enable participants to feel the vibration in advance. On the other hand, the full functionality of the wearable can be ensured (REQ VIB 12).

Table 34: Design Requirements for Vibrotactile Wearables and Warnings

ID	Requirement:	Implementation	Results
REQ VIB 1	Warnings should be possible for the directions: front, back, left, right, and top	4.2.1.2; 4.3.1.2; 5.4	4.2.3.2; 5.9.1; 5.9.1
REQ VIB 2	The wearable should be comfortable to wear and remain lightweight	4.2.1.2; 4.3.1.2; 5.4	4.2.3.2; 5.9.1
REQ VIB 3	The wearable should be unobtrusive for most movements	4.2.1.2; 4.3.1.2; 5.4	4.2.3.2; 5.9.1
REQ VIB 4	The wearable should fit different body sizes	4.2.1.2; 4.3.1.2; 5.4	4.2.3.2; 5.9.1
REQ VIB 5	Vibrotactile warnings should be timely, relevant, unique, diagnostic and advisory, and manageable	5.4	5.9.1;
REQ VIB 6	It should be possible to control vibration parameters separately (vibration area, duration of pulses and pauses, intensity, and repetition)	5.4	5.9.1; 5.9.1; 5.9.2
REQ VIB 7	The meaning of vibration warnings should have a low complexity for safety-critical domains	5.4	5.9.1
REQ VIB 8	The wearable requires a power source to function autarkically	4.2.1.2; 4.3.1.2; 5.4	4.2.3.2; 5.9.1
REQ VIB 9	The control unit of the wearable should allow for wireless communication	4.2.1.2; 4.3.1.2; 5.4	4.2.3.2; 5.9.1
REQ VIB 10	External devices should be able to define each vibration parameter of the wearable	4.3.1.2; 5.4	5.9.1; 5.9.1; 5.9.2
REQ VIB 11	To support mobile and stationary testing an external device should allow logging and monitoring communication of the wearable	4.2.1.2	4.2.3.1; 4.2.3.2; 4.2.3.3
REQ VIB 12	To ensure that the vibration motors are working properly, it should be possible to verify their function separately before a study session	4.2.1.2	-

8.2.3 Evaluating within VR Labs

Design recommendations regarding the testing within VR Labs refer to a more holistic view, including hardware and software components. The requirements, their implementation, and relevant results are listed in Table 35.

Regarding the felt presence (REQ LAB 1), it was found that, in general, the used VR headset (HTC Vive Pro) provided good wearability and immersion capabilities. Even experienced VR users positively highlighted the headset's features, e.g., the headset's comfort, the headphones, or the isolation from the environment (Section 5.9.8). Other factors to consider are the visual environment and the soundscape within the VE. Here, it is recommended to use domain-specific assets (models and sounds) that match the simulation content. Another aspect regarding presence is that the graphical representations of the VR scene do not need to be highly sophisticated to create an appropriate level of presence. This outcome emerged in the study on proximity warnings (Chapter 5), where textures and graphical representations differed in an identical scene.

However, the more sophisticated version left a better impression, increased the perceived level of realism and the overall user experience (Sections 5.9.7; 5.9.8).

Creating scenarios under ethical and moral aspects (REQ LAB 3) was implicitly included in the VEs' modeling. Overall, it is essential to find a compromise between hazard scenarios that appear dangerous to the participants but should not cause flight reactions (see also REQ LAB 15). The ethical perspective will be briefly discussed in Section 8.3.

For the tasks in VR scenarios (REQ LAB 4 and 5), a general recommendation is to use tasks that seem plausible but do not rely on too complex controller interactions, as already stated in Section 8.2.1. A cognitive load measurement based on reaction times has shown that interaction-heavy tasks in VR increase users' cognitive load (Section 4.3.3.4). In contrast, practical tasks with little interaction can seem too simple or even dull (Section 4.2.3.4). Thus, the design of tasks should be a compromise between complexity and purpose. This aspect is also relevant for increasing cognitive load of participants (REQ LAB 6). The results presented in Chapter 4 show that VR locomotion techniques impact cognitive load (cf. REQ LAB 11 and REQ VE 11).

Besides task-based interaction (object grasping, moving, or releasing), the choice of an appropriate locomotion technique is also relevant (REQ LAB 11). The factor 'locomotion' was considered in the first two studies (presented in Sections 4.2 and 4.3). The possibility of enabling real walking (roomscale VR) in a VE was rated very positive by participants (Section 4.2.3.4). The study on locomotion technique comparison (Section 4.3) found that real walking led to shorter reaction times than with controller-based locomotion. Thus, real walking required lower cognitive effort. In other words, real walking increased the user experience and minimized the complexity of interaction with the task in VR. Thus, using real walking as locomotion technique should be considered whenever possible. However, when designing VR scenarios that require a broader landscape, controller-based locomotion is recommended, as it allows not only the use of broader environments but the locomotion technique was also well received by the participants in the presented studies (e.g., Sections 4.2; 4.3; 5.3.1; 6.2.1).

Regarding the network environment and interfaces required in a VR Lab (REQ LAB 7 and 8), it is relevant that every component of the system is tested thoroughly before testing starts. For instance, in the study presenting a mobile test setting (Section 4.2), several data sets were corrupted due to solder joints and cables on the vibrotactile wearable coming loose. To avoid such errors, study facilitators should be able to monitor signals (warnings and responses), enabling them to intervene in the event of errors occurring during testing (see also REQ VIB 11). Additionally, depending on the resources, it is recommended to implement an exact copy of the first hardware prototypes as a backup, which could be used while the other needs maintenance.

Table 35: Design Requirements regarding the VR laboratory

ID	Requirement:	Implementation	Results
REQ LAB 1	The VR scenario should provide a high degree of presence	4.2.1.3; 4.3.1.3; 5.3.1; 6.2.1	4.2.3.4; 5.9.7; 5.9.8; 6.3
REQ LAB 2	The VR laboratory should be able to integrate and (re-)use 3D-models from BIM as VE	-	-
REQ LAB 3	Test scenarios should be ethical and not cause anxiety in participants	5.3.2; 6.2.1	5.8; 5.9.4.2;
REQ LAB 4	Tasks in VR should relate to tasks in the contextual environment of the domain	5.3.2; 6.2.1	5.9.5; 6.3
REQ LAB 5	When testing use cases, real-world conditions should be replicated in VR	6.2.1	6.3
REQ LAB 6	Tasks should demand mental workload without overwhelming participants	4.2.1.1; 4.3.1.1; 5.3.2	4.2.3.3; 4.3.3.3; 5.9.5
REQ LAB 7	Components in the VR laboratory should communicate wirelessly, thus, enabling mobile testing	4.2.1.2	4.3.3
REQ LAB 8	Events in the VE should be transmitted to external wearables	4.2.1.2	4.3.3
REQ LAB 9	Hazard directions in the VE need to be mapped to the warning directions in the wearable	5.3	5.9.4
REQ LAB 10	It should be tested if and how participants' physical activity influences tactile perception	4.2	4.2.3.2; 4.2.3.4
REQ LAB 11	A, for the research purpose, suitable locomotion technique should be implemented	4.2; 4.3; 5.3.1; 6.2.1	4.2.3; 4.3.3.3; 5.9; 6.3
REQ LAB 12	All relevant behavioral data should be logged within VR and screen recording should be used	Implicitly	5.9.4.2
REQ LAB 13	Logging should be done only for data necessary for the research question(s)	-	-
REQ LAB 14	VR-exposure should be kept as short as possible to prevent motion sickness symptoms	5.6	5.9.10
REQ LAB 15	Relevant safety issues with VR should be identified and prevented	-	7.4

When evaluating directional vibration warnings, it is necessary to correctly map the direction of the virtual hazards to the respective vibration areas on the body (REQ LAB 9). With game engines, a possible solution is placing multiple separate collider areas around the user's virtual avatar to notice the direction of approaching objects.

Regarding the impact of physical movements on tactile perception in VR (REQ LAB 10), the study comparing real walking in VR and real environments (Section 4.2) showed that in both conditions resulted in comparable reaction times and accuracy on directional vibration cues.

The VR Lab should also log all necessary data or provide the required methods to log it (REQ LAB 12 and 13). These aspects were dealt with implicitly in the thesis. In general, it can be recommended to include as much data as possible in the studies. For example, a recording of the user with VR hardware should also be captured in addition to a screen recording. These recordings may not need to be analyzed or viewed. Still, they allow to revisit certain scenes, reactions, and interactions afterward. Reviewing the data did help to understand the sequence of happenings in the case of a virtual accident (Section 5.9.4.2). Even if not considered in the thesis, it can be useful to log the individual game flows, i.e., all coordinates of the user and the surrounding objects, to view the respective VEs and scenes virtually in the aftermath.

Last, using a VR Lab should be always hazard-free for study participants (REQ LAB 14 and 15). To avoid motion sickness symptoms, keeping the VR exposure time as short as possible is recommended. However, this recommendation is not conclusive, as although preventing motion sickness was relevant in each study, the studies did not explicitly focus on researching this aspect. For accident prevention, typical accident sequences with VR hardware were analyzed (Chapter 7). As a general recommendation, the VR interaction should avoid participants having to lean too much in one direction, risking losing their balance, and no extreme flight reactions should be triggered.

8.3 Ethical and Privacy Considerations

In the film ‘The Matrix’ (released in 1999), after failing a jumping training session in a simulated training program, the movie’s hero, Neo, notices blood on his hand and asks his mentor Morpheus in disbelief “If you’re killed in the matrix, you die here [in the reality]?”, to which Morpheus answers “A body cannot live without the mind”, indicating the cross-linked worlds. Although this level of interconnection is not given with VR Labs, the movie points out the relevant ethical question of how far the experiences in ‘another reality’ may affect people’s reality, as discussed by Skarbez et al. (2021).

Due to the high immersion capabilities of modern VR systems and the high sense of presence that can be achieved, participants get the feeling of being present in another environment. The study on proximity warnings presented the case of a participant being hit by a vehicle (Section 5.9.4.2). The interview clarified that the participant had already had bad (real) experiences on the road and had been hit in one incident. Thus, she reflected on her real-life experiences with those from the VR experience. On the one hand, VR can help us reflect on similar situations and become aware of them again. Such cases have already been also reported in the study of VR training for safe work with angle grinders, (Chapter 6). On the other hand, one is risking that participants experience negative stress due to the VR scenario. For example, the VR experience could trigger trauma, or participants may get scared by the content and experience anxiety (see analysis of VR-related accidents in Chapter 7). If such traumatic effects are expected to arise in testing a VR simulation, an ethics committee should be consulted when planning VR studies. For the studies within this thesis, no ethics committee was consulted, since no extreme situations were depicted and that the entire research project would therefore be ethically justifiable. Even in the case of the virtual accident of one participant, she assured that this was not a shocking moment (Section 5.9.4.2).

As another important aspect, it may be necessary to consult a data protection expert for such studies, for instance, to re-check the informed consent of studies. In VR Labs, various data sources can be linked depending on the use case. As an example, the VR hardware can store gaze or eye tracking data in addition to motion data. In addition, using external hardware allows to collect and save vital data, such as pulse. The decisive factor is not that such data should not be collected at all but that participants must be adequately informed about and consent to the data collection (the informed consent used in this thesis is attached to Appendix D).

8.4 Socio-technical Aspects of Virtual Reality Laboratories

When implementing VR Labs in organizations, several socio-technical requirements (for the socio-technical perspective, see Section 3.1.2) must be considered. These requirements aim to create VR Labs that are user-centric, secure, precise, and aligned with ethical considerations. Thus, these aspects can contribute to successfully deploying VR Labs in various domains. Here, from a top-down view based on the experiences gained throughout this thesis, four crucial process activities are required for a successful implementation of a VR (as shown in Figure 8.1):

1) Setting up and maintaining the VR hardware
2) Developing and designing adequate VR experiences
3) Preparing and conducting VR studies, and
4) Analyzing the results for the planned outcome

These activities result from the experiences made during this thesis, and they generalize the findings. The first three activities will be described in more detail and reference corresponding sections from which the finding was generalized. The activity "analyze results" will be left out, as this activity relies on many decisions made in the first three activities.

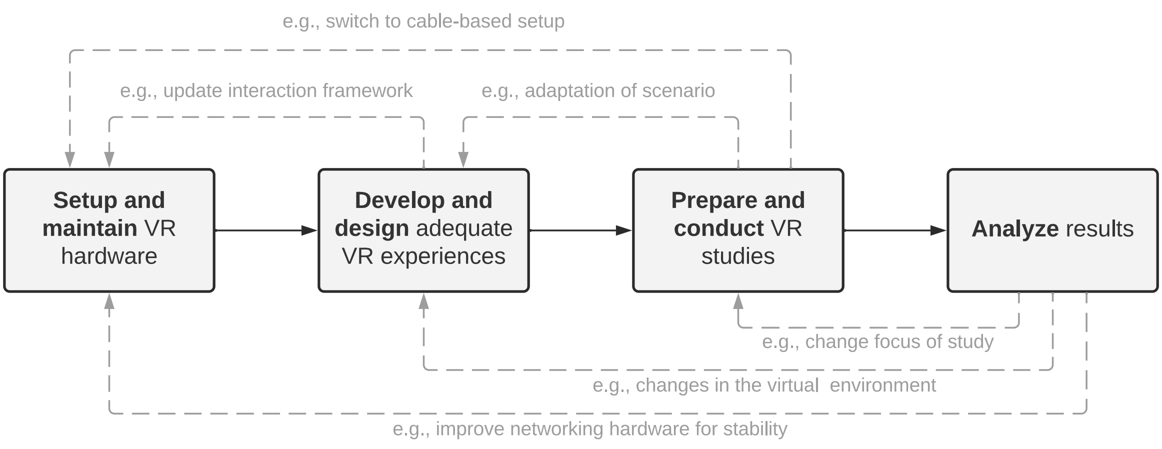

Figure 8.1: Top-Down Process steps required for a VR laboratory implementation

8.4.1 Setup and Maintenance

Several hardware and software components are needed to set up a VR Lab. First, the VR hardware consists of a VR headset and controllers. Depending on the VR system, an external computer that is connected to the VR headset might be needed. If it has to be decided if cable-based or standalone VR headsets should be used, a wireless connection between the headset and the computer should be preferred to prevent users from tripping over the cable. Although participants mentioned a slightly disturbed presence through the cable setup in this thesis (Section 5.9.8). A comparative study by Gonçalves et al. (2020) with 52 participants showed no significant differences between wireless or cable-based VR setups. Another difference between current VR headsets is whether they need external sensors (“base stations”) that track the headsets in space or if they use tracking sensors integrated into the headset. Additionally, as in this thesis, other wearables or microcontrollers must be integrated into the VR Lab. To achieve this, specific interfaces must be implemented to allow communication with the VR hardware.

Second, the software components are needed. These may vary depending on the system and research questions. In general, a VE is required, which may be self-designed and developed, developed by a third party or an existing third-party application. All three solutions have their pros and cons. In general, self-developed VR experiences can be customized as desired and according to requirements, for instance, to implement a communication protocol between a wearable and a VR simulation. However, self-developed VR experiences require many resources and a highly skilled team of software developers, game designers, and others. To reduce the resources needed in self-developed VR experiences, existing 3D- or sound-asset files can be used to design the VE. It may be cost reducing when a third-party company develops the VR simulation on contract.

Regarding the room space for a VR Lab, modern VR systems do not necessarily require special room setups. A neutral and quiet room should be preferred, but since the VR user is isolated from his natural surroundings while using the VR headset, even that preference might be debatable. The two essential requirements for a room are enough space and a screen for the test facilitator. Enough space is needed to allow interaction in VR without hitting objects in the VR Lab and endangering the participants. An analysis of VR-related accidents gathered from the social media platform Reddit has shown that (for domestic settings) in almost 27% of analyzed cases, the environment was unsuitable for VR use and, hence, the reason for an accident with VR hardware (Chapter 7). The screen for the study facilitator is needed to follow the VR users’ actions inside the VE by mirroring the VR view, especially when the user gets stuck at some point and needs support from the study facilitator. Besides room settings, mobile setups are possible. Here, a mobile wireless hotspot is required that allows the hardware to use the communication interfaces, e.g., for data logging.

The maintenance of such a VR Lab requires up-to-date hardware, a stable network, and installing software updates. A stable network is needed to support real-time communication, data streaming, and synchronization, especially in multi-user scenarios. Thus, adequate bandwidth and low latency are crucial to ensure precise data logging and smooth VR experiences.

When external hardware prototypes are used, it must be assured that the developer team can maintain these hardware pieces. For instance, in Section 4.2, two participant data logs were corrupt due to faulty hardware. Depending on resources and prototype complexity, it might be feasible to have a backup prototype ready for use in an early stage that could be used while the other gets maintained.

8.4.2 Development and Design of VR Simulations

Regarding the development and design of VR simulations, a broad contextual understanding of the respective work environments to be simulated is necessary. VEs should visually replicate the work environment and use realistic representations of tools, textures, objects, and machinery. The same applies to the sound in the VE, which should include contextual ambient sounds and use 3D sound to adequately represent approximations of sound sources. Both visual and audio assets can be self-designed or obtained via external providers. However, a fundamental contextual understanding is required to achieve a realistic representation of a real work environment in VR.

Creating close-to-reality and meaningful tasks in the VE is a more challenging process. Due to the controller-based controls, a 1:1 mapping to a real task is usually not feasible. Besides controller interaction, the task implementation is also a negotiation process with other aspects:

- **Data collection**
  The task must reflect research objectives when it comes to data. Collecting a vast data set of specific incidents, such as hazard occurrences. This might require implementing a less realistic task than in the actual work environment, where such hazard incidents would occur less frequently.

- **Task Variety**
  Although a diverse range of tasks and activities would mirror the work environment in more detail, multiple tasks can require a more extended tutorial or training phase of participants, as the controller interaction must be understood before testing. Additionally, multiple tasks would increase development resources.

- **Task complexity**
  Participants usually have no extended training period to train the tasks before experiments/tests. Therefore, too complex tasks requiring a complex interaction can have a measurable impact on the subjective cognitive load of participants and could negatively influence data gathering. However, this might not apply to VR simulations where the task is part of a training.

- **Time Pressure**
  To increase realism and increase the felt stress inside the VE, participants can be put under pressure by explaining to them the need to act fast beforehand or by adding a timer into their view in the VE. Depending on the context, experienced time pressure is part of the working tasks and can impact the subjective workload and quality of work performance.

- **Cognitive Load and Workload**
  Partly overlapping with task complexity and time pressure, it is necessary to understand users' cognitive load to create a task that does not overload their mental capabilities and thus negatively affects the research objective. In contrast to real environments, in VR, users already deal with an artificial way to interact.

- **Social Activities**
  The tasks (and the VE) gain realism when social aspects are integrated into scenes. This can refer to collaborative and cooperative task design with other participants (multi-user VR) or non-player characters (cf. Chapter 6).

8.4.3 Prepare and Conduct Studies

With the experiences gained from the studies during the process of this thesis, this section will outline the steps involved in preparing and conducting studies within a VR laboratory. In the early phase, the research objectives should be addressed. These objectives can differ with each study. In this thesis, the research objectives were:

1) to focus on understanding how a VR laboratory and VR scenarios should be designed,
2) to compare results between VR and reality, and
3) to understand the effect of vibrotactile warnings.

To evaluate design aspects of the components in a VR laboratory and inform the further design process, for instance:

- **Cognitive load analysis to understand the internal components of a VR Lab**
  VR and reality differ in certain aspects. For example, VR uses artificial interaction via controllers. This concerns both the interaction with objects and the locomotion within a VE. It must be understood if and how VR influences task performance.

- **Evaluate the Usability and User Experience of VR Software and Hardware**
  Implementing contextual scenarios in VR requires a trade-off between attention to detail and pragmatism. For example, many shortcomings were noted in the thesis during the VE of the first study (4.2), which were further improved via the follow-up iterations (4.3 and 5). An example regarding the hardware has been shown in Study 4.2, where a Choice-Reaction Time Task has uncovered shortcomings of the wearable that were eliminated in the following version.

To understand the transferability of results from VR to reality:

- **Exploring differences between reality and VR**
  Depending on the research objective, it might be necessary to understand if the used metric behaves the same in both realities. For instance, if wearing VR hardware affects the ability to recognize vibrotactile warnings (Section 5.1).

To evaluate the effect of vibrotactile warnings in a virtual work context:

- **Cognitive load analysis regarding vibrotactile hazard warnings**
  VR Labs allow examining participants' cognitive processes in ecologically valid contexts. Researchers can study human attention, memory, decision-making, and other phenomena with this approach. For instance, to understand the impact of different human-machine interfaces in their contextual use.

- **Behavioral data analysis**
  Due to the immersion in VR simulation-based test environments, human behavior can be analyzed in various scenarios. With VR laboratories, researchers can observe and record how users navigate and interact with the virtual world, capturing data that can be analyzed to gain insights into user behaviors and decision-making processes. For instance, to analyze how participants react to facing reoccurring hazards (Section 5.9.4).

Based on the research objectives, appropriate questionnaires, surveys, or interview guidelines are necessary and, accordingly, be prepared before conducting a study. Besides defining research objectives, suitable hardware must be chosen that serves the overall research objective.

Partly in parallel, participants can be recruited, all needed documents can be prepared (e.g., informed consent), and a pre-run of the study can be prepared. The pre-runs of studies are essential to ensure the whole testing procedure runs without interruptions, bugs in the software (and VE) are removed, and that the data collecting and logging work perfectly. Thus, these pre-runs are vital to ensure the study runs as planned, and they should use an iterative approach to change and recheck any discrepancies until the study runs precisely as intended (see example in section 6.2.1). For the pre-runs, it is optional to recruit any study participants. Instead of recruiting, the participants can be colleagues or similar, as the pre-runs' primary intent is not to generate data but to validate the study procedure. After or during the main study, data analysis and interpretation can start.

8.4.4 Identified Roles in the Process

Based on the analysis of activities and the experiences gained explicitly and implicitly throughout the process of this thesis, a VR laboratory requires a team with diverse expertise to ensure its effective functioning. To give an overview, the following roles should be considered, although not all are *always* necessary. Additionally, roles can overlap in their responsibilities and activities, and multiple roles can be filled out by one person:

- **Laboratory Manager**
  Coordinates and oversees all day-to-day operations of the VR Lab, including resource management, budgets, and schedules.

- **Project Managers**
  Coordinate and oversee the planning and execution of VR projects.

- **Researchers (User-, UX-Researchers)**
  Researchers inform the design process of VR simulations by providing in-depth insights and understanding of the contextual environments. They plan and conduct user studies; thus, they define which data variables are relevant and must be logged for analysis. Depending on the research objective, researchers should be knowledgeable in qualitative and quantitative methods.

- **Participants**
  Participants generally do not need any previous experience with VR as the hardware handling can be learned quickly. However, depending on the research question, it might be necessary to invite participants *with* background knowledge of a specific domain (e.g., safety knowledge on construction sites) if the tasks in the VR scenario require domain knowledge.

- **VR Developers (Game-, Software-Developers)**
  With the designers, VR developers are responsible for creating all VR applications used in the laboratory. They need expertise in VR frameworks and the programming languages used in the frameworks, and expertise in game engines. VR developers also ensure the correct mapping of interactions between VR controllers and actions inside the VR application.

- **Game Designers (Sound-, 3D-, Animation-, Story-Designers)**
  Game designers are responsible for the content of the VR applications, the visual environment, and the soundscape. They create VEs that are encouraging and stimulating to ensure immersive experiences.

- **UX Designers (also UI-, Interaction-Designers)**
  During the design processes, UX designers ensure intuitive interfaces and interaction with the VR application. UX designers incorporate HCI principles in their work process and focus on a good usability of the VR application.

- **IT Support (including System Administrators)**
  The IT support ensures a smooth operation and maintenance of a VR Lab's network infrastructure, hardware, and software. They can provide technical assistance, ensure backup procedures, and support troubleshooting issues.

- **Ethicist / Ethical Reviewer**
  Depending on the study's content, ethical approval might be necessary. An ethical reviewer can ensure ethical guidelines are followed, address potential ethical concerns, and provide documents for informed consent.

- **Data Protection Expert**
  The role of a data protection expert is to ensure all privacy aspects of user data are met. Based on national regulations, a data protection expert can ensure that the VR Lab adheres to relevant regulations or guidelines, can provide documents for the data consent, and define appropriate data collection.

8.4.5 Exemplary Socio-Technical Process for Studies in a VR Laboratory

In Figure 8.2, an outline of an exemplary process for the integration of a VR laboratory in an organization is shown. As process notation, the SeeMe notation is used (see Appendix A). The process focuses on the operative parts and includes a planning activity for the VR laboratory. Planning usually requires a set of different roles to consider many aspects. For instance, such a planning team could involve management, software developers, and researchers to outline the needs and goals of a VR laboratory.

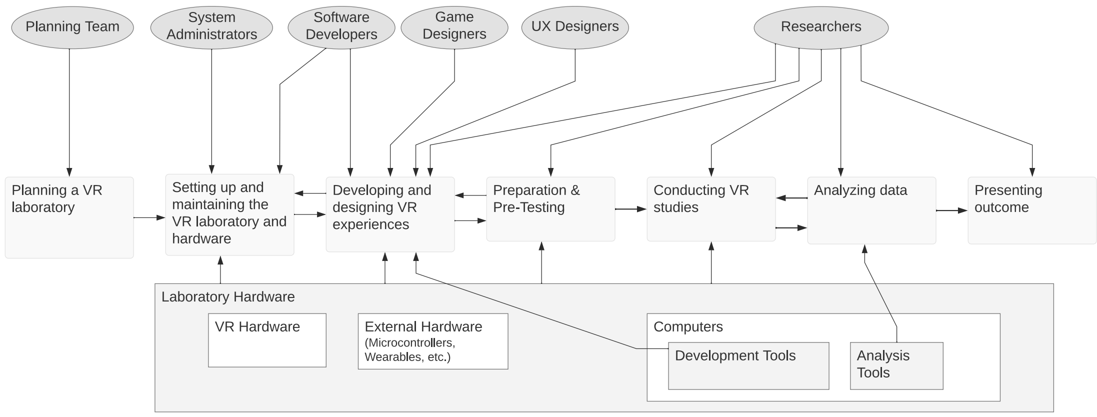

Figure 8.2: Socio-technical process (SeeMe notation) on the use of VR laboratories

After the planning phase, the VR Lab and VR hardware need to be set up for development by system administrators and software developers. The next activity involves developing and designing VR environments. Depending on the domain and previous research, development could include integrating existing BIM 3D models into the VR simulation or re-using existing VEs. In this process step, it might be necessary to define research objectives or contextual requirements and knowledge. Thus, research staff should already be integrated early into this process step and work with developers, game designers, and UX designers.

The next phase outlines the preparation and pre-running of studies/experiments. Depending on the preparation, it might be necessary to change the implementation of the VR experience before going on with the study. Moreover, even during a pre-run, researchers might notice something problematic while checking the data, which could require stepping back and changing the software. For such cases, iterative pre-runs of the study are recommended. The main study should start only when the pre-run shows no need for altering any component. However, when bugs or problems arise within the pre-run, additional changes must be applied to the software and concept until everything runs smoothly. After the study, the collected data will be analyzed and interpreted using statistical or qualitative analysis techniques. In the last activity, outcomes can be presented based on the research questions and analyzed data.

Some elements were omitted in this example process to keep the process diagram lightweight. For instance, the process does not include an ethical review or data protection expert. Their expertise would be required, especially in the study's planning phase, but they could serve as experts along the process. The same applies to system administrators, who are shown only to set up the environment. Depending on the occurrence of unforeseen events, IT support must be considered in each subsequent activity. Another aspect that was left out was the recruiting process of participants. Finally, other versions of this process might want to highlight the interaction between the process steps of "Developing and designing VR experiences" and the "Preparing and conducting VR studies", depending on the complexity of the research question and the data to be collected, the two process steps will mainly run in parallel.

8.5 Evolutionary Outlook for VR Laboratories

Finally, this subsection will provide an outlook on future developments of VR laboratories, even if the statements have a certain degree of uncertainty. The following aspects regarding the evolution of VR laboratories should be considered:

- **Changing regulations of Occupational Safety**
  When guidelines are updated or legal regulations for occupational work safety change, these changes must be reflected in the VR simulations used. Thus, changes that affect existing VR applications have to be implemented. An example of such an effect has been shown in the study on VR safety training in Chapter 6, as the VR simulation did not offer every required PPE needed for working with angle grinders. Although the PPE simply was not implemented in the VR, changing (safety) regulations may result in similar effects, and VR simulations may need to be modified in content to reflect the changes. In addition, safety standards differ between countries (Raheem & Hinze, 2014). When a VR simulation is developed in another country, it should be checked whether the depicted regulations are coherent with the regulations in the own country before applying the simulation in a VR Lab.

- **Impact of Artificial Intelligence (AI)**
  With generative AI, tools are already available that generate 3D objects (Jovanović & Campbell, 2022). With further advancements of such tools, it seems like a matter of time before creating whole VEs with generative AI is possible. Such tools could increase productivity for creating immersive experiences. An example of such an approach is using 3D point clouds from image data to create 3D models of cities (Döllner, 2020). Then, besides generating geometrical data, generative AI can also be used to create more sophisticated virtual characters (NPCs) that can respond to user input dynamically, just as chatbots do. Such approaches are already discussed for educational purposes in immersive learning environments (Balaji et al., 2023) or for VR job interview training (Stanica et al., 2018).

- **Scalability Over Time**
  The scalability of VR Labs must be considered from both the software and hardware sides. The software components are easily scalable to include many

users that can simultaneously experience the same VE, depending on the network bandwidth and infrastructure (Latoschik et al., 2019). Thus, the same software could be distributed and used globally. However, the VR hardware only scales linearly, as each user needs a hardware device to participate.

- **Social VR and Collaborative Task Design**
  Related to scalability, Social VR frameworks enable researchers to create multi-user scenarios in VR and allow to examine collaborative safety scenarios (Le et al., 2015). Depending on the domain and experiment objective, even existing Social VR platforms could be used to conduct remote and collaborative VR experiments (Saffo et al., 2021). For instance, the effects of vibrotactile warnings could be evaluated with several users to investigate how social factors influence behavioral decisions on hazard encounters.

- **Improved Interaction Design**
  With more accurate sensor data and improvements of VR hardware, the interaction design with VEs will increasingly approximate natural interaction. One example is hand tracking in VR, as it brings opportunities for increased immersion (Buckingham, 2021). Then, research is already focusing on increasing haptic feedback mechanisms to allow realistic physical interactions with virtual objects. For instance, the use of haptic gloves (Perret & Vander Poorten, 2018) or prototypes that resemble realistic objects, such as flexible physical connections of VR controllers, to recreate the stiffness of two-handed objects like bows or steering wheels (Strasnick et al., 2018). To create tangible interactions with virtual geometry, Fang et al. (2020) have presented a worn string-based prototype, with strings attached to fingers and the hand, to create tangible interaction. Thus, existing VR Labs and VR simulations might need to be updated to integrate the technological improvements of newer VR hardware.

- **Multi-Sensory Experiences**
  Also adding to the immersive features in VR hardware, the capabilities of multimodal feedback will improve. Besides haptic feedback, other sensory sensations are researched, for instance, to incorporate olfactory feedback into VR (S. Jones & Dawkins, 2018; Richard et al., 2006) or environmental conditions, such as thermal or wind (Ranasinghe et al., 2017). Integrating such technological advances would require additional implementation work for the VR Labs but could improve the overall realism of VR experiences to simulate real-world conditions.

- **Cross-Reality Experiences**
  It is expected that in the future, a seamless transition of Augmented, Mixed, and Virtual Reality will be realized (Jetter et al., 2021; Speicher et al., 2019, p. 5). Cross-reality devices will allow smooth transitions along the boundaries of the reality-virtuality continuum (cf. Section 2.3.1) and enable collaboration between users of different degrees of virtuality (Simeone et al., 2020). Such cross-reality

devices will make it possible to develop scenarios that support all degrees between real and entirely virtual.

In conclusion, VR laboratories will benefit further from technological advancements in VR hardware and software advance over time. However, it can also be noted that technical leaps in hardware can result in regular updates and costs for VR Labs. While the use of VR simulations today can still trigger novelty effects (cf. Section 6.3.4), these effects will fade with widespread saturation of the consumer entertainment mass market, and, if components are not regularly updated, there is a risk that VR simulations for research purposes may quickly seem outdated.

9 Conclusion and Outlook

This final chapter reiterates the contents and findings of this thesis. The contributions to the research questions are highlighted. Then, a critical reflection of the applied research approach is given, discussing limitations and challenges. The chapter concludes with an outlook for future work.

9.1 Synopsis

This thesis examined the application of VR as a laboratory setting for evaluating vibrotactile warning systems in construction site work. After examining the domain and the domain-specific requirements, four areas of research were addressed:

1) Investigating the impact of two locomotion techniques on the detection of vibrotactile cues (Chapter 4),
2) Evaluating directional vibrotactile warnings in the use case of proximity warning systems (Chapter 5),
3) Experiential learning through VR using the example of safe handling of angle grinders (Chapter 6), and
4) General safety considerations in the use of VR (Chapter 7).

Finally, and as a result of the experiences gained during the thesis, the design of VR Labs was addressed, and roles, components, and processes were examined from a socio-technical point of view.

The underlying assumption of using VR for such application purposes was based on the possibility of implementing hazard scenarios in immersive VR. This approach allowed the evaluation of safety warnings and experiential learning with participants without exposing them to real dangers. A major challenge in this regard is the design and implementation of a realistic task that can be used to increase participants' cognitive effort but does not interfere with data measurement and does not overwhelm novice users.

This thesis has shown that VR can serve as a test bed to evaluate systems for human augmentation, such as directional vibrotactile warning systems, which might not yet exist due to their technical complexities or cannot be evaluated effortlessly in realistic settings due to the need for many resources to conduct such studies. VR evaluations are an efficient tool to test and analyze new system prototypes in the early stages of development, thus, before many resources have to be allocated for a real test environment in the lab or field. It has been shown that VR allows evaluating systems that are not yet fully functional, given the present technical possibilities. With VR, their usefulness can be examined, and design criteria can be derived before such systems are used and evaluated in real environments.

It has also been shown that VR is suitable for enabling experiential learning of occupational safety knowledge. In the example of handling angle grinders, this thesis has shown that at least short-term learning effects have been found after participants experienced a VR simulation. In the interviews, participants started to reflect on past situations and experiences based on what they had seen in the VR simulation.

Then, social media data was explored to identify various accident hazards using VR hardware. The analysis showed that for safety aspects of VR Labs, hazards may occur depending on the simulation content and the actions users must take.

9.2 Contributions to the Research Questions

In this section, the main contributions of the thesis shall be related to the respective research questions. For this purpose, the research questions are repeated, and corresponding results are described.

RQ1: What design factors need to be considered to study vibrotactile cues in Virtual Reality?

This research question was addressed in the three studies on vibrotactile cues, either as part of a cognitive load measurement (two studies presented in Sections 4.2 and 4.3) or as directional vibrotactile warnings (Chapter 5). In general, this thesis identified design factors that are VR-specific, specific to vibrotactile feedback, and factors that focus on a rather technical infrastructure allowing communication between VR and vibrotactile devices.

Regarding VR design factors, the locomotion type must be considered when studying vibrotactile (warning) cues. In this thesis, controller-based locomotion and real walking were compared. The focus on locomotion techniques was justified in two aspects: First, for the scenario used here (construction hazards), non-continuous locomotion, like teleportation, could lead to skipping the points of hazards in the VE. Second, because tactile detection may decrease during physical movement like walking, controller-based locomotion was evaluated against real walking. This thesis found that participants' RTs significantly increased when they were physically moving versus standing still, independent of VR or real environment (Section 4.2). Based on the experiences in this study, a comparison of real walking and controller-based locomotion in VR was presented (Section 4.3). Here, results have shown that participants' RTs were influenced by the complexity of interaction controls rather than the locomotion technique. The accuracy of detecting vibrotactile cues was comparable for both locomotion techniques. Thus, based on the results, in a third study investigating directional vibrotactile warnings in VR, controller-based locomotion was used (Chapter 5).

Another VR-specific design aspect is controller interaction to complete tasks. This thesis has shown that participants had significantly longer RTs on vibrotactile cues when using controller-based locomotion in a task requiring a lot of controller interaction (Section 4.3.3). Thus, locomotion and interaction must be considered when designing VR simulations, as both factors will have an influence on task performance. A task was designed that participants felt was conceivable and appropriate for the purpose, but not entirely realistic.

Testing two different graphical fidelities of a VR scenario has shown mixed results, as participants had a better user experience in the realistically looking VE (Section 5.9.1). However, regarding the evaluation of vibrotactile warnings, the graphically low-fidelity version of a VR scene showed comparable results for participants' reaction times.

Then, there are the design factors of vibrotactile feedback parameters: Body placement, duration of vibrations, pauses between vibrations, repetitions, and intensity. In this thesis, vibrotactile cues were applied via a belt around the waist. Using the waist was perceived as unobtrusive and not obstructing during task completion and allowed to display directional vibrotactile signals in cardinal directions and from above (Section 5.9.1).

Besides factors for VR and vibrotactile feedback, the technical infrastructure must be considered. In this thesis, directional vibrotactile warnings started as soon as participants entered a virtual area around objects and places. A mapping of directions between the VE and the wearable must be configured (Section 5.9).

To summarize, in this thesis, the design factors related to:

- VR locomotion technique, revealing that the accuracy to react to vibrotactile warnings was comparable between controller-based locomotion and real walking.
- Task-related interaction complexity, revealing increased RTs with increasing interaction complexity.
- Mapping hazard directions in the VE to the vibrotactile belt, enabling the measurement of reaction times to warnings of hazard occurrences.
- Vibrotactile parameters and body placement, revealing that the used vibrotactile belt was rated as unobtrusive.
- Graphical fidelity of VEs and their impact on vibrotactile warnings, revealing comparable results in RT measurement for both fidelities.

RQ2: What effect have directional vibrotactile warnings on hazard detection in VR?

This research question was mainly explored in the study on vibrotactile proximity warnings (Chapter 5). Even though participants rated the warnings as helpful, they still incorporated the potential severity of hazards into their decisions. Although one virtual accident occurred during the study, several participants reported that they acted more cautiously when crossing the traffic lane at the construction site because of the warnings.

Participants reported that they paid the most attention to vibrotactile warnings coming from directions not in their field of view, i.e., warnings from above, the sides, or behind. In contrast, known hazards or hazards they previously encountered could be anticipated.

Often reoccurring (static) hazards were eventually ignored, even when participants noticed the vibrotactile warning (Section 5.9.4).

However, in some cases, participants had difficulty understanding which hazard was indicated by a warning. Reasons for this were the participants' lack of knowledge about safety on the construction site and different assessments of the severity of the hazards. For the latter case, warnings that indicated a static hazard from above were sometimes not followed up or did not lead to changes in behavior, for instance, protruding materials and equipment on elevations. For mobile hazards, participants became aware of the crane loads hanging above them due to the warning. Here, the results have shown a mixed response from participants, as some responded to stop walking under the load, while others did not change their behavior.

To summarize the contributions to this research question:

- Vibrotactile warnings led to increased attentiveness when crossing traffic routes.
- Repeatedly encountered static hazards were given less attention during the VR simulations.
- Some hazards could not be detected despite directional vibrotactile warning due to a lack of domain knowledge and limited information transmission of vibrotactile warnings.

RQ3: How does the warning detection compare for different vibration parameters (intensity and pattern) as warning signals?

This research question was addressed in the study on vibrotactile proximity warnings (Chapter 5). In general, there were mixed results to this research question. Participants reported that they usually reacted when they noticed a first vibration, independently of the applied pattern. However, the vibration intensity should not be lower than a particular threshold value, as vibrations with a low intensity were not reliably detected during a VR scenario (~67% detection accuracy).

Many different and randomized vibration patterns were used, resulting in too small a data set for each pattern. However, regarding the intensity, the study results showed an increased error rate when the intensity levels of the used vibration motors were lower than 70%.

In total, none of the intensities was unpleasant or painful. Therefore, higher intensities should be preferred to increase the probability of detection when applying vibrotactile warnings. However, the vibration intensity is a compromise between the size and weight of the vibration motor and the control unit with the power supply. The belt used here was rated as unobtrusive by the participants but was also only worn for a short time during the study sessions (Section 5.9.1).

Concerning the number of signal repetitions and the pauses between the signals, it is difficult to make final statements since most participants noticed the vibration at the first occurrence and reacted accordingly. Regarding the body placement of vibration motors, the first study found that the detection performance on the back was noticeably lower than in all other directions. Thus, to increase the detection rates, the number of motors was doubled for an updated version of the vibrotactile belt, and the motors were placed spatially to the left and right of the back column to increase the used back surface.

As a final point, the results showed that interpersonal differences in the RT data could be identified, even within the small sample used in the study. For such observation, it should be examined whether these interpersonal differences could be compensated by using higher vibration intensities or personalized vibration patterns.

In summary, the contributions of this thesis are:

- The VR Lab revealed that intensities beneath 70% of applied intensity resulted in a noticeable decrease in vibration detection accuracy (with the used hardware).
- Observations from the first two studies have shown that VR Labs are suitable for iteratively testing and improving vibrotactile prototypes.
- The approach revealed interpersonal differences in vibration detection and reaction times.

RQ4: What is the impact of experiencing a VR simulation on safety learning and safety knowledge?

This research question was addressed in the study on safety aspects when using angle grinders (Chapter 6). The findings showed that participants were able to increase their knowledge of safety aspects and reflected on their personal experiences. It was also shown that the (learning-)content of the VR simulation should accurately represent reality, as otherwise, there is a risk of acquiring incorrect knowledge.

A pre- and post-VR knowledge test showed that participants acquired (simulation-specific) safety knowledge when working with angle grinders in the VR simulation. However, participants did not critically question the simulation content. After playing the VR simulation, a question on necessary personal protection equipment revealed that participants' answers were based on the equipment that occurred in the simulation. Here, necessary PPE was not considered as required after the VR simulation because it was not implemented and, hence, not shown in the simulation.

Another important aspect was that during the interviews, the participants started to reflect on their experiences in the simulation and compare them with previous experiences from their working life. Connecting their experience to the VR simulation may have been due to the overall realistic task.

In summary, the contributions of this theses to the research question are:

- The VR environment used was also evaluated positively and realistically by people from the target group (trainees in the construction industry).
- Significant increase in short-term knowledge acquisition regarding safety aspects after experiencing a VR safety training.

- Experiencing virtual hazards in a VR safety training triggered reflections in the participants regarding earlier work experiences.
- Omitting relevant safety aspects can lead to participants acquiring incorrect knowledge.

RQ5: How can a suitable VR Laboratory be designed to evaluate vibrotactile warning devices?

This overarching research question was considered with each of the studies presented and their necessary socio-technical components: The first study in Section 4.2 highlighted technical requirements for the VR Lab on performing comparison evaluations between VR and real environments. In the second study in Section 4.3, the requirements for locomotion techniques were discussed by showing the impact of two locomotion techniques on a secondary task measurement. Then, in the study on proximity warnings in Chapter 5, contextual requirements and vibrotactile warnings were studied to perform studies in VR Labs. Chapter 6 has shown how VR Labs can be used to evaluate the learning success of VR safety trainings, before Chapter 7 investigated potential safety issues and hazards when using VR.

To design a suitable VR Lab, it should first be clarified which goal is to be pursued with this lab since the acquisition of hardware depends on the overall research objectives. In the case of this thesis, a standard entertainment VR hardware set consisting of a VR headset, two VR controllers, and four external motion trackers was used and extended with a self-built wearable, utilizing microcontrollers and vibration motors. All studies used the standard VR controllers, apart from the study in Section 4.2, where the participants responded to vibrations via buttons attached to a serving cart. Depending on the application, wearables from external providers can be used. However, self-built wearables provide full flexibility in the design of the wearables and can be configured to own needs.

Then, the most essential factors in the design of a VR Lab to study vibrotactile cues are (additionally to the ones mentioned in RQ1): the VE and task in the VE, the measurement method, and the vibration feedback, whereas the latter was already addressed in RQ3:

- The VEs must integrate exhaustive knowledge of the domain and its domain-specific factors. These factors include the scenario design, legal regulations and recommendations, the visual and auditory design, and the unfolding scenery.
- The task design in VR should resemble realistic tasks but also depend on the research objective. For instance, the study on proximity warnings (Chapter 5) aimed to generate data points directional vibrotactile warnings. As a result, the task design was less focused. Instead, a task was chosen that did generate cognitive load in the participants but, most importantly, focused on generating as many movements in the VE as possible. Thus, the task should be a compromise between what is technically feasible and reasonably plausible. However, when the research objective is to compare performance in VR and reality, the task should

be designed very close to reality. For instance, when transfer learning from VR to real settings is focused, as shown in the VR safety training (Chapter 6).

- To obtain data, a suitable measurement method is indispensable. This thesis applied the dual-task paradigm with a stimulus-response task (a choice-response task in Section 4.2) as secondary task. Comparing participants' performance between a baseline measure and subsequent tasks gives insight into the mental effort the subsequent tasks require. This method also allowed to calculate the accuracy with which the warnings were responded to. Consequently, this method allows the evaluation of different vibration patterns with quantitative data.

As a further aspect, a good technical infrastructure is required for VR Labs, for instance, to avoid time delays in the data transfer of components. The infrastructure is especially important when the VR Lab is temporarily used in other locations, like in external training facilities (Chapter 6).

Finally, relevant safety issues and hazards when testing with VR were analyzed and presented in Chapter 7. Regarding safety aspects, the VR Lab (and the used VE) should refer from triggering fight-or-flight reactions, refrain from requiring participants to strongly lean, and care for a safe hardware and room setup.

In summary, the contributions of this thesis to the research question are:

- The development of a technical environment that allows transmitting warnings from a VE (or other devices) to a wearable for stationary and mobile testing.
- Applying the dual-task paradigm to reveal differences in cognitive load among participants.
- The integration of domain knowledge in the VE and the scenarios using the example of construction site safety.
- An analysis of typical accident hazards when using VR and how they can be avoided in the design of VR Labs.
- The development of a socio-technical process to demonstrate which specialists and which skills are necessary when designing a VR Lab.

9.3 Critical Reflection on the Applied Approach

A major challenge in this thesis was to combine the different approaches and methods from multiple research fields. Designing and using VR Labs of this type requires an extensive skill set, which is ideally enabled by interdisciplinary teams. For instance, required knowledge includes know-how of game engines, implementing specifically for VR, develop vibrotactile wearables, or designing and conducting evaluation studies, among others. In the following, the chosen approach will be critically reflected.

9.3.1 Real World Validity and Task Design

Fundamental to the design of VR evaluation settings of different scenarios is a sufficient analysis of contextual factors in the domain of interest. Based on knowledge gained through observations, scenarios and models were developed and requirements were derived to design VEs. In this thesis, the contextual understanding was gained by observations made during safety inspections in a research project for the construction domain. This knowledge served as a basis for various sources of hazards and to simulate a construction setting. In addition, implications based on a literature review of accident numbers and accident types were integrated to into the VE. Even when the final VEs were not as realistic and detailed as a real construction site, they fulfilled their purpose and allowed participants to feel present in the scene and the overall construction sites were considered to be close-to-reality.

The scenarios and the tasks within the scenarios were a trade-off between interaction complexity and sufficient data generation for the course of this thesis. It remains unanswered whether it would not have been more reasonable to choose a more complex task, which would have involved several work steps and would therefore have been more difficult to solve, while at the same time minimizing the number of potential hazards. In the chosen approach, for instance in the study on proximity warnings (Chapter 5), many hazard encounters were generated, which at the same time could be partially anticipated visually and did not cause any element of surprise. With more complex tasks, a higher degree of cognitive distraction could have been achieved, which in turn could have portrayed the work processes of construction site work more accurately. After all, while construction workers pursue tasks over a longer period of time and constantly have to consider their safety as an additional demand, participants in VR Labs are only exposed to the respective settings for a very short time. However, instead of complex tasks, it is also reasonable to include other realistic distracting tasks, such as answering a phone call while performing a given task or having to talk to a fellow worker. Such communication tasks could not only increase the felt realism in the simulation, but also add a realistic distraction to the overall simulation.

The studies are based on real-world experience, but no exhaustive statement can be made about the ecological validity (Section 2.3.2) of the evaluations, which refers to the transferability of results from test settings to real settings. There is no comparison of an occurred (real) scenario, which could be reproduced in the VR environment and evaluated with participants, to be able to draw comparisons between real testing and virtual testing. Only the study on VR safety trainings (Chapter 6) allows some limited statements on ecological validity, since the study was conducted with trainees from the construction industry, and they had evaluated the task and the setting in terms of realism. In addition, some these participants stated in the interviews that they felt more confident in handling angle grinders after the VR simulation. However, the thesis did not try for transferability between VR and reality, but to understand the design process and review design criteria of such VR laboratory approaches. Additionally, at least in the first study, a proof-of-concept has been shown to what extent the used measurement method could be applied to compare real and virtual settings.

Compared to driving simulators in the automotive domain (e.g., Taheri et al., 2017), VR simulations for other domains seem more complex regarding the interaction inside the simulation. To emulate real-world driving, driving simulators require a few key criteria, such as a steering wheel and gearshift for the haptic component and a virtual road for the visual environment. In VR, with tasks and situations in which people move around to perform activities, design decisions require an adequate locomotion technique, make use of (artificial) mapping of controller buttons for specific interactions or even implement other interaction techniques such as hand tracking.

9.3.2 Virtual Environment and Hazard Severity

The study on vibrotactile PWS in Chapter 5 used near-misses to depict hazards without surprising participants with suddenly occurring accidents. The tasks were also set in such a way that the risk of a virtual accident was very low (although one participant was "run over" by a vehicle, as described in Section 5.9.4.2). Even though the overall hazards were also perceived as such to a large extent, participants were not asked to rate the severity of the shown hazards. For instance, Wogalter, Young et al. (1999) have proposed 8 items to rate the hazard risk, the likelihood of injury, the severity of injury among others (Wogalter, Young, et al., 1999, p. 153). Data gathering with such questionnaires could be used to determine the assessment and evaluation of hazards more systematically and to identify hazards that are perceived as too severe - even if virtual - and should not be included in the scenarios.

Regarding the use case of PWS, only one warning range around hazards was used for testing in the VE. By using different ranges, different PWS systems can be tested with VR Labs (see RQ VIB 15 in Section 3.2.5). However, to replicate real conditions of different systems, data of the respective systems must be recorded in order to simulate them virtually. For example, noise from the warning systems could be incorporated by dynamically changing the colliders used in the VE at runtime.

Another limitation is, that no pre-existing BIM 3D model was used as a basis for the design of the simulation (see REQ LAB 2 in Chapter 3.3). With the integration of BIM in construction projects, existing 3D models can be extracted, converted, and enhanced (textures, sound, etc.) for VR to create a VR simulation on this 3D model. However, there is already existing evidence in the literature to use such approach (Du et al., 2018; Getuli et al., 2020; Graham et al., 2019; Hilfert & König, 2016; Zaker & Coloma, 2018).

9.3.3 Participants

Another limiting factor is that the participants in three studies were mostly students, thus feedback received on the VR construction site should be treated with caution. Further, some of the participants had no prior VR experience, which might lead to rather positive remarks based on novelty effect. This limits their statements in several aspects: First, the view of construction site workers is missing. Experienced workers would probably evaluate certain aspects of the VE differently compared to participants who have never worked in the construction industry. In addition, the respective task within the VR scenes should be tested with participants of the respective domain regarding the implementation and handling of VR input devices. However, in Chapter 6, it was shown that construction work trainees viewed such VR environments similarly positive, even if minor inconsistencies with reality existed.

The statements regarding the vibrotactile warning mechanisms must be questioned by the sample of participants and by missing environmental factors. That said, a complete evaluation of such warning system exceeds the scope of the thesis, as the VR system was not intended to create high acceptance of all users involved and to design a working vibrotactile warning system but was based on investigating the necessary design aspects when creating such VR laboratories.

The overall VR experience and the warning mechanism may be perceived differently by older participants, especially older construction workers that have a great amount of experience and who might ridicule such a system. Dealing with the attitude of older workers towards PPE is a challenge in the construction industry and this aspect also goes beyond the focus of the work. However, this could limit the effectiveness of such lab settings, as other research has shown that promoting behavioral compliance in warning sign effectiveness studies with VR was ineffective when evaluating with older participants of 50-65 years (L. Reis et al., 2015). It also remains open whether the sensitivity of the skin to vibrotactile signals is different for older construction workers. From research it is known, that the sensitivity of the skin declines with age (McIntyre et al., 2021; Verrillo, 1980). However, VR laboratories allow to research such effects and their potential counteractions.

9.3.4 Vibrotactile Warnings

Another limiting factor is the short-term testing of the vibrotactile feedback. Comparable to other research on wearables with tactile feedback (Shull & Damian, 2015, p. 10), the tactile feedback was used for the specific use case of the presented VR studies. Long-term tests for developing and evaluating such wearable devices is crucial, as the long-term usage could have an impact on the design and implementation of such devices. For a stronger validity of the effectiveness of vibrotactile warnings, long-term studies are needed on how workers deal with vibrotactile warnings and whether weakening effects occur, such as habituation to the signals (Section 2.1.1).

In regard to the effectiveness of vibrotactile warnings, the proximity warning study has shown that repetitive warnings for repetitive hazards were less strongly paid attention to. Participants mentioned anticipation of hazards in the sense that while warning signal were acknowledged, participants saw no need to scan the environment for the potential hazard itself. Here it remains open as to whether a more dynamically changing environment will prevent such habituation effects. It also remains to be explored to what extent frequent exposure to vibration signals may ultimately lead to phenomena such as phantom vibration. However, this is an overarching research question for the entirety of vibration research.

In total, it remains unclear whether the vibration strength used would also be sufficiently strong enough in a field test to notice the signals clearly and in time. However, this was not the research objective of this thesis, and such corresponding warning systems for real-world use would have to undergo more extensive testing anyway. In addition, research in the automotive sector has shown that the reduction of visual inattention can also be influenced by thermal feedback and push feedback. As example, in a study by Di Campli San Vito et al. (2019) push feedback had a recognition rate of 100%.

Also, it remains unanswered how vibrotactile feedback compares to other feedback modalities or to other combinations of feedback modalities. For instance, in the field for teleoperation of robotics, Peon and Prattichizzo (2013) have shown that reaction times on vibrotactile feedback were fastest, followed by auditory feedback and visual feedback. From the literature on collision warning systems for automotive systems, Ho et al. (2007) did present a study where a combination of audio-tactile cues led to significantly faster braking responses than solely unimodal signals.

In another study on the comparison of reaction times of different stimulus modalities while standing or walking, Jiang and Hannaford (2015) have shown that, while standing, reaction times were fastest on the auditory feedback, followed by vibration and visual feedback. In their study they compared several body placements for vibration feedback. Reaction times increased significantly on thighs and toes when participants were walking, while the reaction times for the vibration feedback on the waist and wrist did not increase significantly. However, other feedback modalities were left out in this thesis based on the premise that construction site settings are both visually and auditorily stressful. Thus, a VR laboratory setting to evaluate proximity warnings via the tactile sensory channel was designed. However, in terms of augmenting human capabilities, many systems can be envisioned that also project warnings directly onto workers' field of view with the use of augmented reality glasses (e.g., Baek & Choi, 2020). Implementation in VR also made it possible to test prototypes in the field of AR that might not yet be feasible in reality, or that would be technically complex to implement. VR Labs as described in the thesis for the case of vibrotactile warnings allow the evaluation of such systems via a lightweight and resource-friendly approach within virtual simulations.

9.3.5 Social Aspects

In the studies, participants were on their own inside the VR simulation, thus social elements have not been studied. Although some additional NPCs were used, participants have rated it negatively that only a few workers were onsite, which, in addition, were perceived as quite static. In addition, some participants had noted that they would have liked to have more interaction with other characters, for example, to solve subtasks or to work on the tasks together with others.

With appropriate extensions of the VR environment, that allow multiple participants at the same time, social effects could also be investigated. For instance, if participants warn other participants verbally or via gestures after receiving a vibrotactile warning. In the case of proximity warnings, warnings were only tested unidirectionally. However, such warning system should provide a warning not only to the ground worker (the participants in the study) but also to the driver of a construction vehicle approaching the ground worker.

9.4 Outlook

Evaluating prototypes for human augmentation with VR Labs is a promising approach, shown in the example of this thesis of a vibrotactile warning system for the context of dynamic and hazardous working places. For future research, such VR Labs can be addressed for many different use cases and research questions. For example, the differences between task performances in VR and real-world environments could be further explored.

9.4.1 Vibrotactile Warning Systems

For the design of vibrotactile PWS, the extent to which the systems are used over a longer period remains to be examined. On the one hand, it should be clarified which long-term effects occur, whether habituation to the vibrations arises or even phantom vibration occurs. On the other hand, the design should be evaluated to ensure that the systems are not perceived as obtrusive when worn for extended periods of time. Additionally, specific questions could be reviewed. For instance, how workers use the warning system in situations when they are required to work in close proximity to a hazard, and, accordingly, when their attention is already focused on the hazard and the associated task. To prevent constant warnings, a viable approach to handle such situations could be to use an *Intervention User Interface* (Schmidt & Herrmann, 2017) that allows the automated system to be switched off quickly and easily for longer periods of time. In such a case, it could further be investigated whether the existence of intervening functions might lead to general manipulations of the system, i.e., always switch it off.

In future work, different body locations for vibrotactile warnings could be evaluated. Besides warning cues, it could also be evaluated how intervening approaches like the use of electronic muscle stimulation (EMS) could be used to 'push' the worker in the right direction and away from the hazard (e.g., Schneegass et al., 2016; Schneegass & Amft, 2017).

In terms of vibration strength or intensity, comparative testing of different vibrotactile patterns would be necessary to determine thresholds for how strong vibration intensities would be required in settings such as the construction site area. In VR Labs like the one presented in the thesis, there is a lack of environmental factors such as wind, temperature changes, or vibrations emitted by the environment (e.g., of moving vehicles).

Finally, Lab settings can be made more realistic overall if environmental factors were included. The extent to which vibrating platforms are suitable as a means of stimulating tactile sensations simulating ambient vibrations could be examined. Examples in this research direction have been presented by Han et al. (2018), investigating multiple tactile sensations for immersive VR experiences generated by artifacts in the near environment, i.e., by using fans to create wind. Additionally, to increase the extent of haptic sensations in VR, real physical objects could be included into the VR environment. As an example, in their work about *Substitutional Reality*, Simeone et al. (2015) have shown how to integrate the physical environment for the use of two different VR scenes, by mapping the VE to the boundaries of the (physical) objects of a room. Another direction is the use of *Augmented Virtuality* (AV) to integrate real objects into the virtual scene.

9.4.2 Virtual Reality Laboratories and Virtual Environments

Participants experienced the VR simulations alone and completed the task individually. Thus, the simulations could be extended and evaluated over several stages. First, collaboration on a task with non-player characters could be implemented to give participants a stronger sense of being part of the virtual scenario. Second, with the advances on multi-user VR platforms (Social VR), the settings could be extended to allow multiple participants interact simultaneously in the same VE, even with different roles and tasks. In such a setting, participants would be able to complete their own tasks or work collaboratively on assignments, adding a more realistic feel to the VR simulation. With such a social VR experience, the warning systems can also be evaluated on a social level, for example, whether the vibration warning is also verbally passed on to other workers in the surroundings.

With the capabilities of Generative AI, it is also possible to create NPCs that can interact with users with far exceeding capabilities of prefabricated NPCs. An example for such application is the use of NPCs with AI on the training for job interviews in VR (Stanica et al., 2018). In general, it would be worth exploring how generative AI could be meaningfully applied in such scenarios and what effect it would have on participants and task completion.

Then, at least when no additional hardware is needed other than the VR hardware, VR Labs profit from the fact that they allow remote studies as long as the participant has access to a device. However, with re-locating the evaluation location into the homes of participants, the safety aspects listed in Chapter 7 regain importance. An example of conducting remote studies in VR has been shown by Saffo et al. (2021). The authors argue that recruiting VR users was easier and that they could replicate studies, indicating a high research validity of remote VR testing.

9.5 Concluding Remarks

This thesis introduced the use of VR systems as a method to evaluate directional on-body vibrotactile warnings. After outlining the design space and the requirements for the approach of a "VR Lab", the research was structured into four areas: "Cognitive Workload and Perception in VR", "Vibrotactile Proximity Warnings and Behavior Change", "Virtual Reality Safety Training", and "Safety Aspects of Virtual Reality".

In the first area, the impact of VR and VR typical locomotion techniques on the cognitive effort of participants and their ability to detect vibrotactile cues was evaluated. In the second area, directional vibrotactile warnings were evaluated for the use case of proximity warnings. After that, the impact of VR safety training on knowledge acquisition was evaluated. Lastly, the safety aspects of using VR for research were analyzed using social media data. Based on the experiences in the four areas, a socio-technical analysis of planning and operating VR Labs was presented. It was shown that both planning and operating VR Labs is a complex task and requires a high technical skill set, but also that VR Labs have a huge potential, allowing the evaluation of all kinds of scenarios, even if they are not yet feasible in reality.

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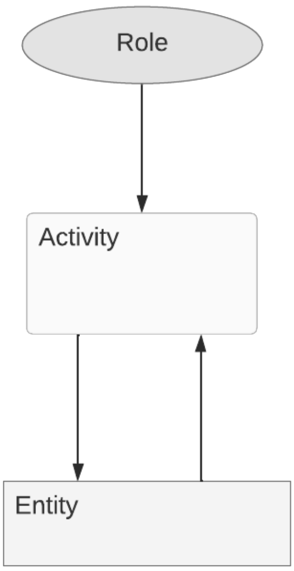
List of Acronyms

AI	Artificial Intelligence
ANOVA	Analysis of Variance
AR	Augmented Reality
AV	Augmented Virtuality
BG	Berufsgenossenschaft (employers' liability insurance association)
BIM	Building Information Modeling
BMI	Body Mass Index
CAVE	Cave Automatic Virtual Environment
CC	Creative Commons
C-HIP	Communication-Human Information Processing
CLT	Cognitive Load Theory
CRT	Choice Reaction Time
DGUV	Deutsche Gesetzliche Unfallversicherung (German Social Accident Insurance)
EEG	Electroencephalography
EEMUA	Engineering Equipment and Materials Users Association
EMS	Electrical Muscle Stimulation
ERM	Eccentric Rotation Mass
GPS	Global Positioning System
HA	Human Augmentics
HCI	Human-Computer Interaction
HMD	Head-Mounted Device
iPQ	iGroup Presence Questionnaire
MD	Median
MR	Mixed Reality
MRT	Multiple Resource Theory
NPC	Non-Player Character
NIOSH	National Institute for Occupational Safety and Health
PDS	Person Detection System
PPE	Personal Protection Equipment
PWS	Proximity Warning System
RPM	Revolutions per Minute
RT	Reaction Time
RV	Reality-Virtuality
SD	Standard Deviation
SSQ	Simulator Sickness Questionnaire
STF	Slip, Trip and Fall
SUS	System Usability Scale
TLX	Task-Load Index
UEQ	User Experience Questionnaire
UI	User Interface
UX	User Experience
VE	Virtual Environment
VR	Virtual Reality

Appendix

A. SeeMe Process Modeling Notation: Base Elements

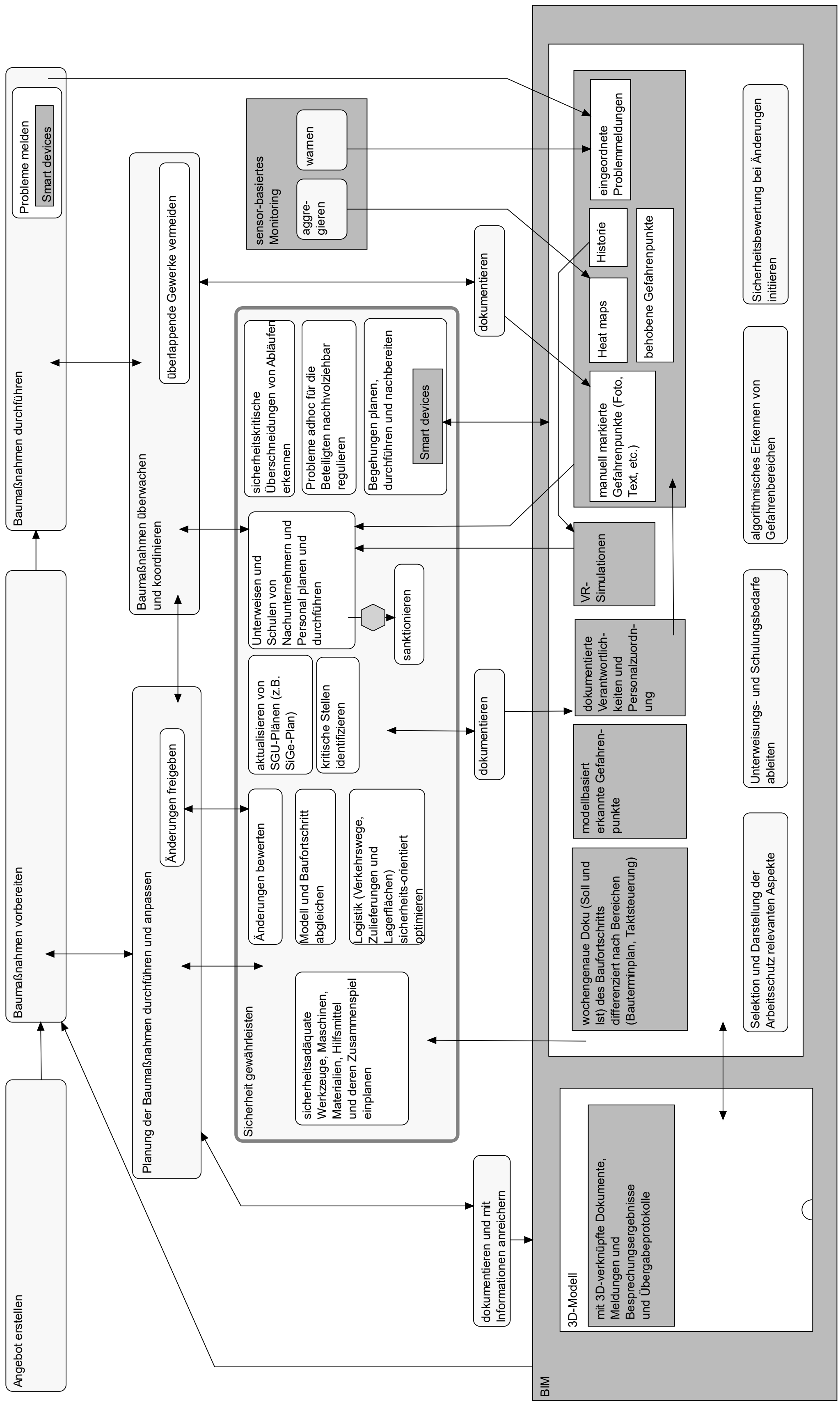
SeeMe is a semi-structured process modeling method. Compared to other process modeling methods, SeeMe has a simpler structure and is therefore easy to use and intuitively comprehensible even for people with no modeling experience after a brief explanation. The intuitive structuring makes the method suitable for use in modeling workshops. SeeMe is characterized by three basic elements, the so-called base elements: Roles, Activities and Entities. Additionally, there are relations to relate elements to each other. Roles represent persons, teams, or organizations. For roles, the question of participation in activities arises in a process. Ultimately, a role must cover a set of rights and duties, which can therefore be assigned to a person, a department, a work group or other organizational units.



Arrows (relations), represent relationships between different elements. Depending on the elements that are connected, the type of a relation changes. While an arrow from a role to an activity describes an execution, for example, an arrow from an entity to an activity represents a usage.

For a full overview over the SeeMe notation, refer to Herrmann (2009).

B. TARGET Construction Process (in German)



C. Interview Guideline for the Study Comparing Real Walking in VR and Real Environments

Introduction

- General question about well-being, e.g., motion sickness symptoms
- What previous experience do you have with virtual reality?
- What previous experience with construction sites and working on construction sites?
- How did you feel about wearing the VR **headset**?

Virtual Reality Environment

- How realistic did you think the task was?
- Was there anything that you felt was unrealistic?
    - o If no answer: how about, e.g., missing arms, legs?
- How did you feel about being able to move freely in VR?
- Are there things you would want to change about the VR environment?
    - o If no answer: e.g., add vehicles, more footage?
- How did you feel about using the serving cart in VR?
    - o Was it distracting?
    - o Did it fit into the context?

Input Method

- How did you feel about the input method via the four buttons?
- Do you think that you made incorrect reactions to the vibrations?

Perceived Vibrations

- How well did you feel the vibrations on your body?
    - o Do you think they need to be stronger?
    - o Were they unpleasant?
- Could you hear the vibrations?
- How did you feel about wearing the belt?
- Do you think something should be changed about the belt?
    - o Ask for examples.

Before Ending the Interview

Was there anything else that stood out to you that you would like to share?

D. Informed Consent (in German)

Studienteilnahme „TactVR“ T-ID: ______________

Einverständniserklärung für Versuchsteilnehmer am Lehrstuhl Informations- und Technikmanagement

Ich wurde von der durchführenden Person für die oben genannte Studie vollständig über den Inhalt, die Bedeutung und Tragweite der Studie aufgeklärt. Ich wurde darüber informiert, dass es im Zusammenhang mit dem Tragen von Virtual Reality Brillen in ca. der Hälfte der Fälle zu Motion Sickness (Schwindel, Kopfschmerzen, Übelkeit, etc.) kommen kann. Ich wurde darüber aufgeklärt, dass ich im Falle von Motion Sickness, die Brille absetzen und das Training abbrechen darf. Weiterhin wurde ich darauf hingewiesen, dass innerhalb der Studie auch Video- und Audiodaten aufgenommen werden können und dass ich die Option habe, einzelnen Aufnahmen zu widersprechen.

Ich hatte die Möglichkeit, Fragen zu stellen. Ich habe den Versuchsablauf sowie die damit einhergehende Erhebung und Verarbeitung meiner Daten verstanden und akzeptiere sie. Ich bin über die mit der Teilnahme an der Studie verbundenen Risiken und auch über den möglichen Nutzen informiert wurden. Ich hatte ausreichend Zeit, mich für eine Beteiligung an der Studie zu entscheiden und weiß, dass die Mitwirkung freiwillig ist. Ich wurde darüber aufgeklärt, dass ich jederzeit und ohne Angabe von Gründen diese Zustimmung widerrufen kann, ohne dass dadurch Nachteile für mich entstehen. Mir ist bekannt, dass meine Daten anonym gespeichert und ausschließlich für wissenschaftliche Zwecke von dem Lehrstuhl Informations- und Technikmanagement der Ruhr-Universität Bochum verwendet werden.

Bitte ankreuzen:

- ☐ Ich erkläre hiermit meine freiwillige Teilnahme an dieser Studie.
- ☐ Ich stimme zu, dass Eyetracking-, Audio-, Bild- und Videodaten von mir für die Studie aufgenommen werden dürfen.
- ☐ Ich erkläre mich hiermit einverstanden, dass meine Daten **anonymisiert** für die Studie und Veröffentlichungen weiterverarbeitet, analysiert und ausgewertet werden dürfen.

Optional:

- ☐ Ich stimme zu, dass Bilddateien auf denen Ausschnitte von mir (außer dem Gesicht) von meiner Teilnahme in wissenschaftlichen Veröffentlichungen veröffentlicht werden dürfen.
- ☐ Ich stimme zu, dass Bilddateien auf denen zu sehen ist, wie ich die VR-Brille trage (d.h. Teile meines Gesichts sind zu sehen, u.a. Mund, Kinn oder Mundschutz) in wissenschaftlichen Veröffentlichungen veröffentlicht werden dürfen.

Name (Druckbuchstaben)	
E-Mail (optional)	
Datum	
Unterschrift	

E. Demographics Questionnaire (in German)

Studienteilnahme „TactVR" T-ID: ___________

Fragen zur Person

Alter: _____ Jahre

Gewicht: ___ kg

Größe: ____cm

Geschlecht:

☐ weiblich

☐ männlich

☐ _____________

Aktuelle Tätigkeit:

☐ Student, Studiengang: ____________________

☐ Berufstätig, als __________________________

☐ ____________________________

Benötigte Sehkorrektur:

☐ keine ☐ ja, nämlich: ________________________

Händigkeit:

☐ rechtshändig ☐ linkshändig ☐ beidhändig

Vorerfahrungen mit Virtual Reality:

☐ Gar keine (noch nie benutzt)

☐ Gelegentlich (weniger als 5 Mal ausprobiert oder Gesamtspielzeit < 2h)

☐ Gut (über 5-mal ausprobiert oder Gesamtspielzeit zwischen 2 und 10h)

☐ Sehr gut (oft ausprobiert oder Gesamtspielzeit > 10h)

☐ „Experte" (z.B. Besitz eigener VR-Hardware oder selbst etwas mit VR entwickelt)

Teilnehmer-ID:

1) Anfangsbuchstabe Ihres Geburtsortes: _____
2) Anfangsbuchstabe eigener Vorname: _____
3) Eigener Geburtsmonat (als Zahl zweistellig): _____
4) Anfangsbuchstabe des Vornamens der Mutter: _____

F. Nasa-Task Load Index (German Version)

TactVR: NASA-TLX T-ID: __________ Durchgang: __________

Beanspruchungshöhe
Geben Sie jetzt für jede der untenstehenden Dimensionen an, wie hoch die Beanspruchung war. Markieren Sie dazu bitte auf den folgenden Skalen, in welchem Maße Sie sich in den sechs genannten Dimensionen von der Aufgabe beansprucht oder gefordert gesehen haben:

Beispiel:

X

gering hoch

Geistige Anforderungen
Wie viel geistige Anstrengung war bei der Informationsaufnahme und -verarbeitung erforderlich (z.B. Denken, Entscheiden, Rechnen, Erinnern, Hinsehen, Suchen...)? War die Aufgabe leicht oder anspruchsvoll, einfach oder komplex, erforderte sie hohe Genauigkeit oder war sie fehlertolerant?

gering hoch

Körperliche Anforderungen
Wie viel körperliche Aktivität war erforderlich (z.B. Ziehen, Drücken, Drehen, Steuern, Aktivieren, ...)? War die Aufgabe leicht oder schwer, einfach oder anstrengend, erholsam oder mühselig?

gering hoch

Zeitliche Anforderungen
Wie viel Zeitdruck empfanden Sie hinsichtlich der Häufigkeit oder dem Takt, mit dem Aufgaben oder Aufgabenelemente auftraten? War die Abfolge langsam und geruhsam oder schnell und hektisch?

gering hoch

Leistung
Wie erfolgreich haben Sie Ihrer Meinung nach die vom Versuchsleiter (oder Ihnen selbst) gesetzten Ziele erreicht? Wie zufrieden waren Sie mit Ihrer Leistung bei der Verfolgung dieser Ziele?

gering hoch

Anstrengung
Wie hart mussten sie arbeiten, um Ihren Grad an Aufgabenerfüllung zu erreichen?

gering hoch

Frustration
Wie unsicher, entmutigt, irritiert, gestresst und verärgert (versus sicher, bestätigt, zufrieden, entspannt und zufrieden mit sich selbst) fühlten Sie sich während der Aufgabe?

gering hoch

Kontrollieren sie bitte, ob Sie zu allen Fragen Angaben gemacht haben. Bei Unklarheiten wenden Sie sich bitte an die Versuchsleiterin / den Versuchsleiter.

G. iGroup Presence Questionnaire (German Version)

TactVR T-ID: ___________ Durchgang: ______________

Fragebogen zum Präsenzgefühl in virtuellen Welten

Sie sehen nun 14 Fragen bzw. Aussagen darüber, wie und was Sie erlebten. Bitte geben Sie jeweils an, ob die Aussage zutrifft oder nicht. Sie können die gesamte Breite der Antwortmöglichkeiten nutzen. Es gibt keine richtigen oder falschen Antworten, es zählt nur Ihre Meinung.

Ihnen wird auffallen, dass sich manche Fragen sehr ähneln; das ist aus *statistischen Gründen* notwendig - wir bitten um Verständnis. Und bitte denken Sie daran: beantworten Sie alle Fragen jeweils in Bezug auf dieses *eine* Erlebnis.

Ich hatte nicht das Gefühl, in dem virtuellen Raum zu sein.

Hatte nicht das Gefühl	-3	-2	-1	0	+1	+2	+3	Hatte das Gefühl

Wie sehr glich Ihr Erleben der virtuellen Umgebung dem Erleben einer realen Umgebung?

Überhaupt nicht	-3	-2	-1	0	+1	+2	+3	vollständig

Ich hatte das Gefühl, in dem virtuellen Raum zu handeln statt etwas von außen zu bedienen.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

Wie real erschien Ihnen die virtuelle Umgebung?

Vollkommen real	-3	-2	-1	0	+1	+2	+3	Gar nicht real

Ich hatte das Gefühl, das die virtuelle Umgebung hinter mir weitergeht.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

Ich hatte das Gefühl, nur Bilder zu sehen.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

Wie bewusst war Ihnen die reale Welt, während Sie sich durch die virtuelle Welt bewegten (z.B. Geräusche, Raumtemperatur, andere Personen etc.)?

Extrem bewusst	-3	-2	-1	0	+1	+2	+3	unbewusst

TactVR T-ID: ____________ Durchgang: ______________

Meine Aufmerksamkeit war von der virtuellen Welt völlig in Bann gezogen.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

Die virtuelle Welt erschien mir wirklicher als die reale Welt.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

Wie real erschien Ihnen die virtuelle Welt?

Wie eine vorgestellte Welt	-3	-2	-1	0	+1	+2	+3	Nicht zu unterscheiden von der realen Welt

Meine reale Umgebung war mir nicht mehr bewusst.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

In der computererzeugten Welt hatte ich den Eindruck, dort gewesen zu sein…

Überhaupt nicht	-3	-2	-1	0	+1	+2	+3	vollständig

Ich fühlte mich im virtuellen Raum anwesend.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

Ich achtete noch auf die reale Umgebung.

Trifft gar nicht zu	-3	-2	-1	0	+1	+2	+3	Trifft völlig zu

H. Simulator Sickness Questionnaire (German Version)

Studienteilnahme „TactVR" T-ID: ___________ PRE / POST

Simulator Sickness Questionnaire

Kennedy, Lane, Berbaum, &Lilienthal (1993)

Symptom \ Häufigkeit	Gar nicht	Etwas	Mittel	Stark
Allgemeines Unwohlsein				
Müdigkeit				
Kopfschmerzen				
Überanstrengung der Augen				
Probleme scharf zu sehen				
Erhöhter Speichelfluss				
Schwitzen				
Übelkeit				
Konzentrationsschwierigkeiten				
Kopfdruck				
Verschwommenes Sehen				
Schwindel (Augen auf)				
Schwindel (Augen zu)				
Gleichgewichtsstörung				
Magen macht sich bemerkbar				
Aufstoßen				

I. System Usability Scale (German Version)

Fragebogen zur System-Gebrauchstauglichkeit

1. Ich denke, dass ich das System gerne häufig benutzen würde.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

2. Ich fand das System unnötig komplex.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

3. Ich fand das System einfach zu benutzen.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

4. Ich glaube, ich würde die Hilfe einer technisch versierten Person benötigen, um das System benutzen zu können.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

5. Ich fand, die verschiedenen Funktionen in diesem System waren gut integriert.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

6. Ich denke, das System enthielt zu viele Inkonsistenzen.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

7. Ich kann mir vorstellen, dass die meisten Menschen den Umgang mit diesem System sehr schnell lernen.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

8. Ich fand das System sehr umständlich zu nutzen.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

9. Ich fühlte mich bei der Benutzung des Systems sehr sicher.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

10. Ich musste eine Menge lernen, bevor ich anfangen konnte das System zu verwenden.

Stimme überhaupt nicht zu 1	2	3	4	Stimme voll zu 5
○	○	○	○	○

J. Interview Guideline for the Vibrotactile PWS Study

Introduction

- Question about well-being, e.g., motion sickness symptoms?
- How did you feel about wearing the VR headset?
- Do you have prior experience with VR?
- Do you have prior experiences with construction sites?

Input & Interaction

- How well did you get along with the controls?
- Do you think you made any mistakes when reacting to the vibrations? (If yes, why)

Virtual Reality: Task and Environment

- How realistic did you perceive the task?
- Was there anything that you felt was unrealistic?
    - If no answer: e.g., missing arms, legs? Collecting objects?
- Are there things you would want to change about the VR environment?
    - E.g., add vehicles, more staff, objects?
- How did you perceive the soundscape?
- Query:
    1. did you notice the road with moving vehicles?
    2. did you notice the airplanes?
    3. did you notice the helmet you were wearing?

Hazard Spots

- Which hazards and hazard spots did you notice? Scenarios 1-3
  (In the meantime, show the screenshots and go through them with the participants)
- Which of the mentioned hazards did you also perceive as dangerous, which ones rather not?

Vibrations

- How well did you feel the vibrations on your body?
    - Should it be more intensive or was it unpleasant?
- Did you notice a certain direction of the vibration particularly well?
- How did you feel about the belt? (Wearing comfort?)
- In your opinion, should something be changed about the belt?

Before ending the Interview

Is there anything else that stood out to you that you would like to share?

K. Tactile Questionnaire (in German)

TactVR: Baseline-Erhebung - Reizinterpretation T-ID: ___________

Taktile Reize

Geben Sie an, wie Sie die taktilen Reizsignale interpretiert haben.

Zur Erzeugung der taktilen Reize nutzt der Bauchgürtel mehrere Vibrationsmotoren. Geben Sie bitte an, wie viele Vibrationsmotoren (nicht Anzahl an Vibrationen) Sie pro Richtung erkannt haben oder vermuten:

Vorne: ____________

Links: ____________

Rechts: ____________

Hinten: ____________

Reizinterpretation

Der taktile Reiz deutet an, dass ich mich in die Richtung des Reizes bewegen soll.

Stimme nicht zu	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	Stimme zu

Der taktile Reiz deutet an, dass sich etwas aus der Richtung des Reizes auf mich zu bewegt.

Stimme nicht zu	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	Stimme zu

Der taktile Reiz deutet an, dass sich in der Richtung ein Objekt befindet.

Stimme nicht zu	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	Stimme zu

Der taktile Reiz deutet an, dass mich an der Stelle etwas berührt.

Stimme nicht zu	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	Stimme zu

Der taktile Reiz deutet an, dass sich in der Richtung kein Objekt befindet.

Stimme nicht zu	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	Stimme zu

L. Construction Site Safety Questionnaire (in German)

*Der vorliegende Fragebogen befasst sich mit verschiedenen Aspekten zum Thema **Arbeit auf Baustellen**. Bitte füllen Sie den Fragebogen nach bestem Wissen und Gewissen aus. Bei mehr als zwei Antwortmöglichkeiten, können auch mehrere Optionen angekreuzt werden.*

Nr.	Frage	Richtig	Falsch
1	Auf Baustellen darf Baumaterial kurzzeitig auf Gerüsten gelagert werden.		
2	Auf Baustellen müssen LKWs beim Rückwärtsfahren jedes Mal eingewiesen werden.		
3	Winkelschleifer dürfen einhändig geführt werden, um herabfallendes Material aufzufangen.		
4	Kettensägen dürfen auf Baustellen nur mit Gehörschutz eingesetzt werden.		
5	Bei Fahrzeugen auf Baustellen ist immer der Fahrer des Fahrzeuges für die Sicherheit anderer verantwortlich.		
6	Als Bauarbeiter ist es mir bei fehlendem Seitenschutz nur angeseilt erlaubt, auf einem Gerüst zu arbeiten.		
7	Ich bin der Meinung, Winkelschleifer dürfen ausnahmsweise einhändig geführt werden, wenn man sich z.B. auf der Leiter festhalten muss.		
8	Ordnung ist auf einer Baustelle aus Sicherheitsgründen jeder Zeit zu gewährleisten.		
9	Der Konsum von Alkohol in Arbeitspausen kann von der Bauleitung ausnahmsweise genehmigt werden.		
10	Das Tragen von Handschuhen ist bei der Arbeit mit Winkelschleifern erforderlich.		
11	Bei sehr heißem Wetter darf man auch ohne Sicherheitsweste auf Baustellen arbeiten, so lange man nicht über die Baustelle läuft.		
13	Um mich auf der Baustelle zu bewegen, sollte ich immer die vorgesehenen Verkehrswege benutzen.		
14	Das Tragen von Handschuhen ist bei der Arbeit mit Kreissägen materialabhängig.		
15	Es reicht, einmal am Tag meinen Arbeitsbereich zu kontrollieren und abzusichern.		
16	Schutzhauben von Kreissägen dürfen abmontiert werden, wenn das zu bearbeitende Material sich mit der Haube verklemmen könnte.		
17	Winkelschleifer ohne Schutzhaube dürfen unter gar keinen Umständen verwendet werden.		
18	Ich darf mit meinem Privat-PKW in Notfällen auf der Baustelle herumfahren.		
19	Ich darf mich in die Schaufel des Baggers setzen, wenn dies die einzige Möglichkeit ist, eine schwer zugängliche Stelle zu erreichen.		
20	Linkshänder können einen Winkelschleifer auf der Baustelle einsetzen, ohne den Seitengriff zu nutzen.		
21	Fahrbare Arbeitsbühnen dürfen bewegt werden, wenn derjenige, der auf der Bühne steht, gewarnt wurde und sich sichtbar festhält.		
22	Unfälle auf Baustellen müssen nur dann gemeldet werden, wenn eine Verletzung die Arbeitsfähigkeit beeinträchtigt.		
23	Für Arbeiten an schwer zugänglichen Stellen kann die Schutzhaube abmontiert werden, wenn dadurch der Winkelschleifer freier beweglich ist.		

Nr.	Frage	Richtig	Falsch
24	Ich darf mich an das Seil eines Krans hängen, um Kollegen, die in einer Notlage sind, zu helfen.		
25	Trennscheiben können bei der Nutzung von Winkelschleifern ohne jegliches vorherige Anzeichen zerspringen.		
26	Für fahrende Fahrzeuge auf Baustellen muss ich auch dann besondere Rücksicht und Aufmerksamkeit haben, wenn die Nutzung eines Werkzeugs volle Konzentration erfordert.		
27	Wenn ein Kollege an einem Verkehrsweg mit einem Winkelschleifer arbeitet, sollte ich einen alternativen Verkehrsweg benutzen.		
28	Sperriges Material darf auf Verkehrswegen zwecks Wechsel der Transportmaschine abgestellt werden, ohne Alternativwege anzubieten.		
29	Bei Wartungsarbeiten an einer Bohrmaschine sollte unbedingt vorher der Stecker des Stromkabels gezogen werden.		
30	Es ist nur bei schweren Arbeiten wichtig, einen Winkelschleifer an den vorhandenen Griffen beidhändig zu führen.		
31	Im Fall einer Personenrettung darf ich auch ohne Einweisung einen Kran auf der Baustelle bedienen.		
32	Bei Arbeiten mit Winkelschleifern können Personen von wegfliegenden Teilen getroffen werden.		
33	Andere Personen auf der Baustelle sind immer für ihre eigene Sicherheit verantwortlich.		
34	Sneaker und Turnschuhe sind nur für ganz spezielle Aufgaben für die Arbeit auf Baustellen geeignet.		
35	Straßenverkehr muss immer an der Baustelle vorbeigeleitet werden.		
36	Ich bin der Meinung, dass Winkelschleifer ohne Seitengriff in Ausnahmen verwendet werden können.		
37	Um schwer zugängliche Stellen auf der Baustelle zu erreichen, darf ich die vorgeschriebenen Verkehrswege verlassen.		

12. Worauf muss man bei Scheiben für Winkelschleifer achten? (Mehrfach-Antworten möglich!)
- ☐ Die Scheibe muss für das zu trennende Material zugelassen sein
- ☐ Die Scheibe muss in die Schutzhaube passen
- ☐ Ablaufdatum der Scheibe darf nicht überschritten sein
- ☐ Keine der drei genannten Punkte

38. Bei Arbeiten mit Winkelschleifern auf einer Baustelle benötigt man folgende persönliche Schutzausrüstung (PSA) (Mehrfach-Antworten möglich!):
- ☐ Schutzbrille
- ☐ Helm
- ☐ Sicherheitsschuhe / Schutzschuhe
- ☐ Handschuhe
- ☐ Gehörschutz
- ☐ Atemschutz
- ☐ Man darf auch ohne PSA mit einem Winkelschleifer arbeiten

Note. The numbering of the items is listed as used in the study. The multiple-choice questions are listed here separately due to the tabular format.

M. Interview Guideline: Experiential Learning Safety Training

Before the interview:

- Ask whether an audio device may be used and make sure it is running!
- Ask, how the person is doing.
- Briefly explain what the interview is about and that there are no wrong answers.
- Explain, that the interview can be stopped at any time.
- Always ask for examples and in the course of the interview always come back to the examples during the interview.

1) Introduction and Background of the Person

- How did you feel about wearing the VR headset?
- Did you feel signs of sickness or dizziness while playing the game?
- Were the controls of the game clear to understand?
- What is your relationship to working on construction sites?
- Do you have experience using power tools/motorized hand tools?
  - o How often do you use power tools?
- What (prior) experience do you have on the subject of occupational safety/occupational health?
  - o In relation to construction sites?
- What previous experience do you have with Virtual Reality

2) Simulation Content

- What do you think the VR simulation was about?
- Was it clear to you what you had to do in the simulation?
  - o Were there any ambiguities? If so, what were they?
- How did you perceive the start of the game?
  - o Would you have liked further instructions?
- What criteria did you use to select your safety helmet?
  - o Did you recognize a difference between the helmets offered?
- According to which criteria did you select the angle grinder?
  - o Did you recognize a difference between the offered angle grinders?
- Did you make any mistakes in the simulation?
  - o Which mistakes and why?
  - o After the mistake, were you aware of what you should have changed/how you could have avoided the mistake?

3) Visualization in the VR Simulation

- How realistic did you find the VR simulation?
  - o Were there things that you found very unrealistic?
- Were the textual representations easy to read?
- What did you like about the simulation? What did you notice in a positive way?
- What did you not like about the simulation? What did you notice negatively?
- Were there situations in which you would have liked more feedback or instructions?

4) **Built up beliefs**
   - How confident do you feel about the training for future use of an angle grinder or similar tools?
   - What would you do if others told you that you were about to work with an angle grinder for the first time?
   - How would you respond if someone else claimed that safety measures on the job site were excessive?
   - What would you do if you observed several people ignoring such safeguards?
   - Would you get involved in an argument with the people involved if the safety measures were ignored?

5) **Other**
   - Do you have any other comments, criticisms, recommendations about the VR simulation?

N. Data for the Accident Analysis from r/VRtoER

ID	Category	**Submission ID** reddit.com/r/VRtoER/comments/SubmissionID
1	Immersion	gl3rbt
2	Misuse of hardware (fake/staged)	ha3vvd
3	Immersion	kinmzg
4	Invasion of VR space	ndk09e
5	Immersion	m2rhnt
6	Immersion	jm5na6
8	Immersion	j62om5
10	Immersion	d6g96c
11	Hardware not properly used	t99olp
12	Immersion	nymtid
13	Room space not suitable	gla79q
14	Immersion	em21cb
15	Room space not suitable	n5edhb
17	Invasion of VR space	ew69oj
19	Immersion	ete8ue
20	Invasion of VR space	ecwqhm
23	Room space not suitable	en5oxp
24	Spectator engagement	jlfo97
25	Immersion	luwh8v
28	Spectator engagement	r6zw8f
29	Hardware not properly used	d4wp6t
31	Room space not suitable	ke8pio
33	Misuse of hardware (fake/staged)	reyd42
35	Immersion	k33loq
36	Sensory Motor Problem	icvmyl
37	Probably faked/staged	m1a4ed
38	Room space not suitable	d3w2ci
39	Hardware not properly used	hht04k
40	Misuse of hardware (fake/staged)	p1kcvf
41	Immersion	jnqb8x
42	Room space not suitable	hjdku6
45	Misuse of hardware (fake/staged)	qygtsg
46	Room space not suitable	k9hczb
49	Room space not suitable	jcfq3m
51	Immersion	tt53kz
52	Invasion of VR space	rydnq4
53	Sensory Motor Problem	gl60q3
54	Sensory Motor Problem	ki0sqz
55	Immersion	Xtzamn
56	Spectator engagement	n0vksh
57	Immersion	t5baru
58	Room space not suitable	fpcdm8
60	Invasion of VR space	pitxqz
62	Sensory Motor Problem	eferys
63	Probably faked/staged	o5i8vl

ID	Category	Submission ID: reddit.com/r/VRtoER/comments/[SubmissionID]
64	Immersion	jlmx0c
65	Sensory Motor Problem	mmwfii
66	Sensory Motor Problem	mr0gew
68	Room space not suitable	neoyir
69	Immersion	i2omke
72	Spectator engagement	fuo2eu
73	Room space not suitable	jt5y3i
76	Immersion	shwqd5
77	Probably faked/staged	loz3e0
78	Misuse of hardware (Fake/Staged)	t2rhji
79	Misuse of hardware (Fake/Staged)	glgqpx
80	Room space not suitable	sij24v
82	Invasion of VR space	pkdaur
83	Room space not suitable	gyhwjc
85	Unknown	t9yb0a
86	Probably faked/staged	osc7x5
87	Sensory Motor Problem	i9mqcg
92	Sensory Motor Problem	s99rew
93	Immersion	hlaxg9
95	Immersion	ujt9ax
96	Sensory Motor Problem	p53q5f
97	Room space not suitable	knpspi
99	Room space not suitable	m1ud5r
101	Spectator engagement	rp0d98
102	Sensory Motor Problem	jiqf2z
105	Sensory Motor Problem	kzeie7
107	Probably faked/staged	ubjg5q
108	Sensory Motor Problem	tco0vy
111	Immersion	eqh4ua
113	Room space not suitable	gimnuf
114	Room space not suitable	py8asq
120	Unknown	nw71e8
126	Invasion of VR space	xilqr4
129	Invasion of VR space	grwbny
133	Immersion	w8ixm3
140	Sensory Motor Problem	bmxg5a
144	Immersion	sask8i
151	Sensory Motor Problem	o19h45
157	Sensory Motor Problem	e3gd3w

ID	**Category**	**Submission ID: reddit.com/r/VRtoER/comments/[SubmissionID]**
162	Sensory Motor Problem	fn9tzs
168	Room space not suitable	qzezk3
170	Room space not suitable	cs8zar
171	Room space not suitable	tljedm
172	Immersion	ohdvur
173	Immersion	qzw7bo
174	Immersion	lcj0yr
176	Immersion	kxbxcb
184	Room space not suitable	f8tlk6
185	Room space not suitable	j16lnb

Eidesstattliche Erklärung zu § 14 Abs. 1 Nr. 6

Ich gebe folgende eidesstattliche Erklärung ab:

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbständig ohne unzulässige Hilfe Dritter verfasst, keine anderen als die angegebenen Quellen und Hilfsmittel benutzt und alle wörtlich oder inhaltlich übernommenen Stellen unter der Angabe der Quelle als solche gekennzeichnet habe.

Die Grundsätze für die Sicherung guter wissenschaftlicher Praxis an der Universität Duisburg-Essen sind beachtet worden.

Ich habe die Arbeit keiner anderen Stelle zu Prüfungszwecken vorgelegt.

Haltern am See, 03.10.2023

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Markus Jelonek