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The Virtual Hand and Beyond

Analyzing Factors of Embodiment and Development of Alternative Input Techniques

Dissertation

submitted to the Universität Hamburg
Faculty of Mathematics, Informatics and Natural Sciences
Department of Informatics

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2025

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Date of Disputation:	06-10-2025

Abstract

A natural way to interact with our environment is to use the hands, such as for object manipulation when using a pen or a fork or communicating with others via gesturing or signing. While for many years head-mounted displays (HMDs) could only be operated with specific motion controllers, in the last few years more and more devices also support built-in hand tracking to provide a more natural way of interacting inside the virtual environment (VE). Such virtual hands can feel incredibly real: When a virtual hand is exposed to a potential threat, electroencephalography (EEG) measures show patterns that are similar to threat reactions on one's own body [90]. In the context of virtual reality (VR), this illusion is known as Sense of Embodiment (SoE).

This thesis investigates interaction techniques in VR that concern the hands in two ways. First, we explore possible influencing factors of the virtual hand illusion: The appearance of virtual hands, in terms of realism (ranging from abstract, like a floating sphere, to photorealistic) and anthropomorphism (ranging from less humanoid to human), as well as the role of redirection sensitivity towards redirected hand motions. In the second part, we then consider novel ways how interaction with HMDs can be done beyond hand-based input. Here we investigate the role of the secondary hand in bimanual tasks, and we explore how other body parts, like the feet, could be used to interact in VEs.

Keywords: Virtual Reality, Virtual Hand Illusion, Embodiment, Hand Redirection, Input Technique, EMG

Zusammenfassung

Eine natürliche Art, mit unserer Umwelt zu interagieren, ist der Einsatz der Hände, z.B. bei der Handhabung von Gegenständen, beim Gebrauch eines Stifts oder einer Gabel oder bei der Kommunikation mit anderen durch Gesten oder Gebärden. Während Head-Mounted Displays (HMDs) lange Zeit nur mit speziellen Controllern bedient werden konnten, unterstützen immer mehr Geräte auch integriertes *hand tracking*, um eine natürlichere Art der Interaktion in der virtuellen Umgebung zu ermöglichen. Solche virtuellen Hände können sich unglaublich real anfühlen: Wenn eine virtuelle Hand einer potenziellen Bedrohung ausgesetzt ist, zeigen Elektroenzephalographie (EEG)-Messungen Muster, die der Reaktion auf die Bedrohung des eigenen Körpers ähneln [90]. Im Kontext von Virtueller Realität (VR) wird diese Illusion als Sense of Embodiment (SoE) bezeichnet.

In dieser Arbeit werden Interaktionstechniken in VR, die die Hände betreffen, auf zwei Arten untersucht. Erstens erforschen wir mögliche Einflussfaktoren der virtuellen Handillusion: das Erscheinungsbild der virtuellen Hände in Bezug auf Realismus (von abstrakt, wie eine schwebende Kugel, hin zu fotorealistisch) und Anthropomorphismus (von wenig humanoid hin zu menschlich), sowie die Rolle der Sensitivität gegenüber Bewegungsveränderung zwischen realer und virtueller Hand. Im zweiten Teil betrachten wir dann neue Wege, wie die Interaktion mit HMDs über die handbasierte Eingabe hinaus erfolgen kann. Hier untersuchen wir die Rolle der zweiten Hand bei zweihändigen Aufgaben und erforschen, wie andere Körperteile, z.B. die Füße, für die Interaktion in virtuellen Umgebungen genutzt werden können.

Stichwörter: Virtuelle Realität, Virtuelle Handillusion, Embodiment, Bewegungsveränderung, Eingabetechnik, EMG

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Part I

Background

1

Introduction

There is no reason why the objects displayed by a computer have to follow the ordinary rules of physical reality with which we are familiar.

Ivan Sutherland, The Ultimate Display [250]

1.1 Motivation

We perceive our environment and our body with the help of various sensory organs, such as the eyes for vision, the ears for hearing as well as balance, and the skin for touch and temperature. From birth on, we learn to make sense of these multisensory cues and how we need to move our body, the head, the eyes, the legs, and the arms to interact with the world: grab an object like a glass of water, walk on two feet, or communicate with voice, gestures, and mimics [4]. We are highly trained to use our body, and we know its visual appearance very well: Most people could probably identify an image of their hands from several other hands imminently.

VR strives to immerse users into virtual worlds that can be experienced with various senses. Head-mounted displays (HMDs) can offer a large field of view of up to 130° and a refresh rate of up to 144 Hz, as in the Valve Index[1], and also a high resolution of up to 3840 × 3744 per eye, as in the Varjo XR4[2]. Such HMDs usually provide tracking in 6 degrees of freedom (DOF), covering the head pose as well as the users' movement inside the tracking space, like turning or walking. However, the *physical reality* as we know it does not need to be replicated in VEs: in VR, visiting the moon [245], fictive places [21] or even time travel [80] are possible.

Hands are an important part of our body, as they are not only used for grabbing but also play an essential role in communication, such as pointing to specify a place or object or performing gestures for supporting speech, or they can be used for signing [11]. The hand is highly complex, consisting of 27 bones [226] that form five digits: four fingers and the thumb. It is controlled by 33 muscles, which are mostly located in the forearm and

[1] https://www.valvesoftware.com/de/index
[2] https://varjo.com/products/xr-4/

connected to the bones via tendons. The hand is innervated by three nerves that control the motor function and transport the sensory information to the brain. In the brain, the importance of the hands is highlighted by the large areas of both the sensory and motor cortex that are dedicated to the hands only [92, 199].

Identifying the own body and its posture appears to be easy and straightforward. However, the body schema, the representation of our body and its configuration in space, has been found to be highly adaptable [99]. This is necessary, as our body changes a lot during the lifespan, from a newborn to a grown adult, or can incorporate changes of the body like the loss of a limb or body weight changes. Also, it has been shown that tools can be incorporated into the body schema, such that the tip of the tool is represented in the brain areas that were previously linked to hand position [123].

Including not only a tool, but a fake hand into the body schema was first described by Botvinick et al. [29], who induced a feeling of illusionary ownership over a rubber hand by providing synchronous paintbrush strokes on both the participant's hand and a rubber hand while the participant's own hand was invisible to the participant. The illusion is based on multisensory integration, a process of the nervous system to integrate multiple sensory information into a coherent perception [243]. Multisensory integration is stronger when the sensory stimuli arise temporally and spatially close to each other [140, 179, 180]. The rubber hand illusion could also be induced in an immersive VR setup, using a similar study design [143, 237]. It has been shown that threatening such a virtual hand causes a similar reaction in the brain as when the own body is threatened [90].

Yuan and Steed [281] showed that a virtual hand can also feel real without the visuo-tactile synchrony (brush stroking) from the original setup: The participants performed tasks with virtual hands that were controlled by hand-held motion controllers. The users' reactions to virtually treating the hands varied with the visual appearance of the virtual hand (humanoid or arrow) but were stable after applying a gradually increasing offset between the real and virtual hand.

The feeling that the virtual hand is one's own hand, also known as Sense of Ownership (SoO), is part of the concept of *embodiment* or Sense of Embodiment (SoE), i.e., the sense of "being inside, having, and controlling a body" [136]. Embodiment also includes Sense of Agency (SoA), describing the feeling of controlling the avatar's actions, and Self-Location (SL), the place where one feels to be located [136]. These subcomponents have both unique and shared factors and thus are interconnected [31, 96, 97]

Many up-to-date HMDs provide markerless hand tracking via optical, markerless tracking technology, which makes it possible to interact with virtual objects similarly to how we are used to interacting in the real world. It has been found that the virtual hand illusion is easier to induce when the virtual hands are controlled directly, as we are used to, rather than via controllers [3, 158, 261], as both the movement and the tactile feedback are closer to the virtual hand, making the multisensory integration easier. Furthermore, hand tracking has been found to be preferred by users over controller input, even if it is less efficient [131, 158, 263].

By manipulating the hand movement data before visualizing it in the VE, an experience can be created that diverges from the *physical reality with which we are familiar*. This can be useful to make interacting in VR more comfortable and efficient [70, 87, 122, 178, 183] or to apply it in rehabilitation [274]. Such redirections can stay unnoticed when they are small enough [65, 88, 284, 285].

Another important factor for a convincing virtual hand illusion is the visual appearance of the virtual hands, which can be more or less realistic, anthropomorphic, and truthful, thus resembling the own hands more or less. In recent applications, virtual hands are often quite abstract (i.e., white, such as in the Oculus XR hands package; see Figure 1.1, left). Depending on the context, hands can also be designed to fit the environment, such as the hands in Half-Life: Alyx that are visualized wearing special gloves; see Figure 1.1, right. This, however, makes the multimodal integration harder, as the visual impression of wearing gloves does not fit the tactile perception when the user does actually not wear gloves.

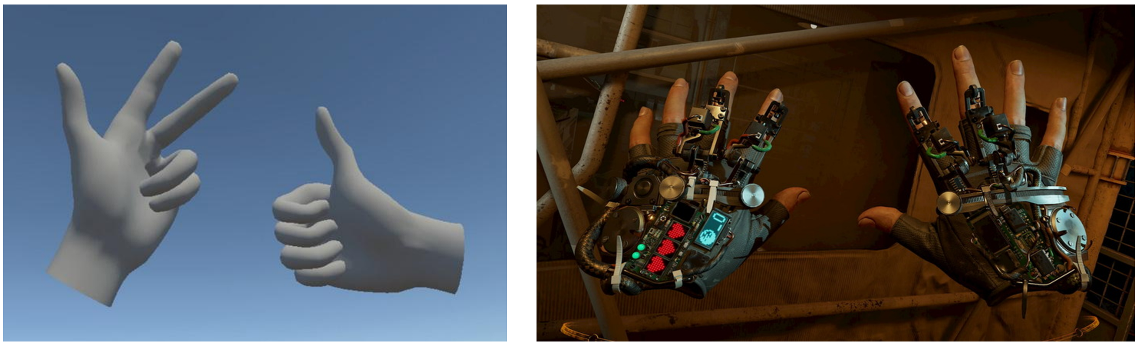

Figure 1.1: Different virtual hand appearances: (left) virtual hands from the Unity XR Hands package[3] © 2023 Unity Technologies, licensed under CC BY-NC-ND 4.0[4] and (right) virtual hands from Valve's Half-Life: Alyx[5].

But VR offers possibilities beyond *the ordinary rules of physical reality* that allow us to create a "reality" that purposely diverges from the real world. This property of VR is particularly of interest in the context of diversity, such as gender diversity and diversity of the body [55]. In this context, immersionists, in contrast to augmentationists, see the VE as a parallel world that is disconnected from their real life [241]. With the advent of the *Metaverse*, a three-dimensional online environment in which users are represented by avatars [214], the question of how users want to present themselves there is becoming more and more important. Another way the *ordinary rules of physical reality* can be enhanced in VR relates to the input mechanics of such systems. Hand-based interaction is not preferred, or even possible, for everyone. Reasons for this are manifold and can include both temporary conditions, like a broken arm or movement restrictions that can appear due to illness or aging, as well as chronic conditions, such as the absence of fingers,

[3] https://docs.unity3d.com/Packages/com.unity.xr.hands@1.1/manual/index.html
[4] https://creativecommons.org/licenses/by-nc-nd/4.0/
[5] https://www.half-life.com/de/alyx

hands, or arms. While PCs and gaming consoles are relatively open to adjusting the input methods as needed with custom input and output devices [273], consumer-level VR HMDs usually are closed systems that only allow the provided input mechanics (usually motion controllers or hand tracking) that heavily rely on two fully functional hands [85]. To make VR more accessible to everyone, more diverse input methods are necessary.

Therefore, this thesis investigates the question of how we want to interact in the virtual world: How can we design a convincing virtual hand illusion, and how can VR become more diverse in terms of avatar appearance and input methods?

1.2 Transregional Collaborative Research Centre Crossmodal Learning

The research for this thesis was conducted within the scope of the Transregional Collaborative Research Centre "Crossmodal Learning—Adaptivity, Prediction, and Interaction" (CML), an interdisciplinary initiative in the fields of artificial intelligence, psychology, and neuroscience. It was launched in 2016 and renewed in 2020 and was founded by the Deutsche Forschungsgemeinschaft (DFG) and Natural Science Foundation of China (NSFC) as an international collaboration between the University of Hamburg, the Medical Center Hamburg Eppendorf (UKE), Tsinghua University, Beijing Normal University, Peking University, and the Institute of Psychology of the Chinese Academy of Sciences. The long-term goal of the research center was "to develop a framework describing the neural, cognitive, and computational mechanisms of crossmodal learning"[6].

The project was divided into four thematic areas: A—Dynamics of Crossmodal Adaption, B—Generalization and Prediction, C—Human-Machine Interaction, and Z—Integration Initiatives and Demonstrators. This thesis contributes to Area C, which had the goal to "investigate crossmodal learning from the perspective of human-machine interaction, addressing issues that specifically relate to the shared multimodal signals that are perceived by both human and machine."

Inside this area, this work was conducted in Project C8, "Crossmodal bindings and plasticity during visual-haptic interaction for novel forms of therapy," which was divided into three tasks. This work covers the first task, "Virtual Upper Limb Presentation," researching the effect of avatar upper limb appearance on SoO and SoA and to what extent deviations between motion of the real and virtual upper limbs affect SoO and SoA. Task 2 covered neurological foundations of pain and touch processing and examined to what extent pain patients show detrimental vibro-tactile performance and thus improve performance of vibro-tactile perception as a result of enhanced SoO and SoA and demonstrate the efficacy for rehabilitation. Finally, Task 3 aimed at extending these approaches to patients with phantom limb pain and complex regional pain syndrome (CRPS) to examine

[6] https://www.crossmodal-learning.org/home.html

the generalization and neural plasticity of the intervention across different tasks and syndromes.

1.3 Research Outline and Structure

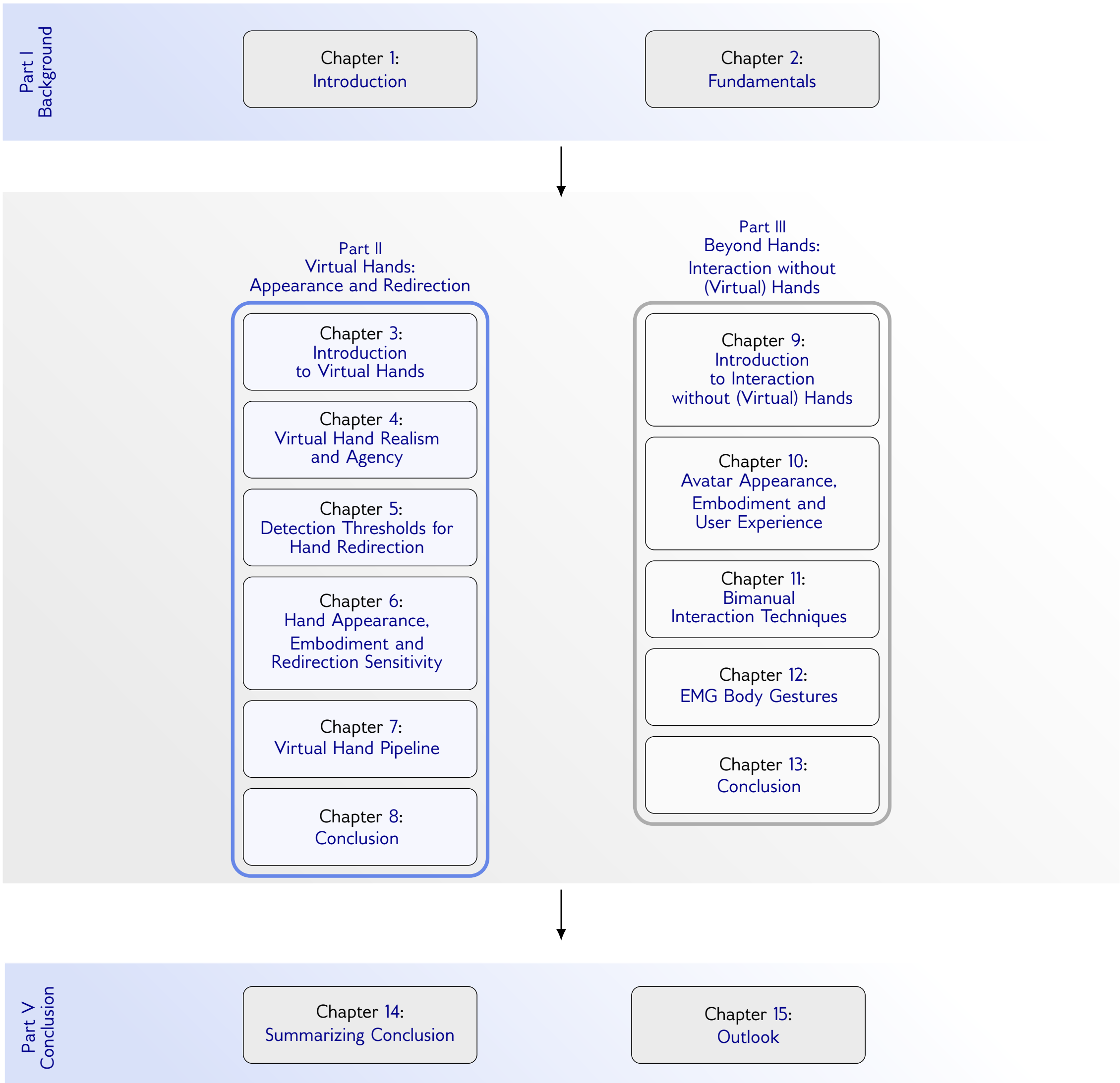

Figure 1.2: Structural overview of this work.[7]

The main goal of this thesis is to improve interaction in immersive VR setups, with a special focus on two aspects: Firstly, by investigating embodying a virtual body, especially virtual hands, and secondly, by developing and evaluating alternative input methods for HMDs.

This thesis is divided into four parts; see Figure 1.2. Part I introduces the topic (see Chapter 1) and gives an overview of the most important concepts (see Chapter 2). Part II explores the effect of hand appearance and hand redirection on the SoE. When we interact

[7]Thanks to Tim Rolff for sharing his template for this figure and helping to adapt it.

with people or objects in the real world, we usually use our hands. So fully articulated virtual hands are an intuitive way to interact in the real world. Also, we are used to seeing our hands in the way we know them and expect them to move as we are used to. Both the appearance and movement of the virtual hand can diverge from the real-world experience. The amount in how far both appearance and redirection contribute to the convincing virtual hand illusion is not clear yet. This research is guided by RQ1, which is further introduced in Chapter 3:

- **RQ1**: How do appearance and redirection contribute to the virtual hand illusion?

However, the appearance can differ between contexts, ranging from more artificial to photorealistic appearances. The role of virtual hand realism on SoA, a building block of the embodiment illusion, is still unclear. While in the field of human-computer interaction (HCI), questionnaires for SoE and SoA are established; we contribute by applying an objective measure, the intentional binding (IB) paradigm, to answer RQ1.1:

- **RQ1.1**: Does virtual hand realism influence Sense of Agency?

RQ1.1 is investigated in Chapter 4, which is based on Hartfill et al. [106]. While our findings show IB for both tested hand models, we could not find an effect for hand realism, suggesting that other factors of hand visual fidelity than realism play a role in agency, such as anthropomorphism.

In another line of research, the movement manipulation techniques have been applied to virtual hands to enhance interaction space or improve ergonomics [183, 205]. In VR, it can be beneficial to increase the interaction space or enhance ergonomics. We contribute to a more in-depth understanding by investigating hand redirection with hand-tracking technology on three spatial axes and both hands to answer RQ1.2:

- **RQ1.2**: Do motion direction and handedness influence redirection sensitivity?

Chapter 5, which is based on Hartfill et al. [108] presents a study to answer this research question. We found detection thresholds for hand redirection between 0.522 and 0.727, depending on movement direction, and significant differences for redirection sensitivity between movement directions.

We then combine both lines of research, investigating the interplay of hand appearance on redirection sensitivity, hypothesizing that more realistic virtual hands increase the redirection sensitivity, as people would expect more natural virtual hand movements with more realistic hand appearance. Moreover, we included hand models with varying anthropomorphism and tested the effect on embodiment. This leads to RQ1.3:

- **RQ1.3**: Does embodiment influence redirection sensitivity?

This research question is investigated in Chapter 6, which is based on Hartfill et al. [112]. We did not find an effect of hand appearance on redirection sensitivity. However, regarding embodiment, we found that embodiment was significantly lower for both abstract hand models with limited degrees of freedom (DoFs) compared to both the anthropomorphic hand models, supporting our findings from Chapter 4. While we did find that the used hand models elicited different levels of embodiment, no effect on redirection sensitivity could be found; we hypothesize that there is no direct link between the two.

In all previously presented studies, the used hand models varied in appearance from artificial to more realistic but never reached a level of photorealism that is truthful to the user's real hand appearance. Chapter 7 presents an outlook on a pipeline for generating such fully articulated virtual hand models that can be integrated from data acquisition to inclusion in a Unity scene within 30 minutes [111]. Chapter 8 summarizes and concludes the findings from Part II.

In Part III of this thesis, we investigate concepts beyond the use of hands and their virtual counterparts, acknowledging the diversity of human bodies by investigating the role of self-representation for virtual whole-body avatars and exploring novel ways to perform bimanual tasks and interact without hand input at all.

Part III of this thesis is guided by RQ2, which is elaborated in Chapter 9:

- **RQ2**: How can XR interaction systems be designed for the diverse human body in terms of virtual representation and input techniques beyond the hand?

While in Part II we investigated the effect of realism and anthropomorphism in the virtual hand illusion, we did not investigate whether truthfulness has an effect on embodying virtual hands. However, when using a whole-body avatar, in many applications users can decide on its appearance and create an avatar that is more similar to their actual appearances or does not resemble them at all. Whether truthfulness and self-representation have an effect on embodiment is formulated in RQ2.1:

- **RQ2.1**: What effect do truthfulness and self-representation have on embodiment?

Chapter 10, which is based on Hartfill et al. [107], explores this research question. While standard embodiment questionnaires did not reveal a significant effect between a generic (G), a photo-generated (PG), and a self-configured (SC) avatar, we did find higher attractiveness and valence ratings, as well as an increased threat reaction in the SC condition. So self-representation may not be reflected in embodiment but does seem to alter the attitude and perception of the user towards their own avatar.

Regarding input techniques, HMDs usually offer handheld motion controllers or hand tracking for interaction within the VE. Both these technologies are designed for fully functional hands with five fingers and without motion impairments in mind [85]. Additionally, the applications often expect bimanual interaction, like operating a virtual gun or having specific tasks for both hands. A deviation from this assumption can make it hard or even impossible to participate in such virtual worlds, even if the condition is temporary, like a broken arm. Even with novel technologies like eye gaze input, as in the Apple Vision Pro, the confirmation of the selection is done using a hand gesture.

To explore novel input techniques for the diverse human body, we first investigate bimanual tasks in VR by exploring input techniques with limited responsibility for the secondary hand to answer RQ2.2:

- **RQ2.2**: What role does the secondary hand have in VR?

This research question is investigated in Chapter 11, which is based on Hartfill et al. [110]. In a user-centered design process, we developed 3 prototypes for alternative input techniques with varying levels of responsibility in the secondary hand, using a wireless electromyography (EMG) system. We evaluated these techniques in two ways: First, we conducted a larger-scale user study with 26 participants to assess baseline metrics on the efficiency and usability. We found that those interaction methods can be as efficient as unimanual interactions, even without prior learning, showing the potential of electromyography and motion tracking for bimanual interaction in VR. Second, feedback was gathered from four participants with unilateral upper limb impairments to refine the prototypes and identify accessibility barriers in the design. Results of the thematic analysis indicate that people with upper limb differences appreciated the proposed bimanual interaction techniques.

In the scope of that work, we found that using EMG technology was easy to learn for most participants. So we further explored ways in which this concept might be useful by combining EMG confirmation with eye gaze selection. Here we were especially interested in how other body parts apart from the arms could be used for input in HMD systems [105], answering RQ2.3:

- **RQ2.3**: How does EMG-based input compare to traditional pinch gestures in terms of task efficiency, user experience, and cognitive load in user interactions?

This work is presented in Chapter 12, which is based on Hartfill et al. [112]. In a pre-study, we investigated user preference for four different body gestures for eye gaze confirmation. We selected the two most preferred ones and compared them to a camera-based tracking gesture (Pinching). While participants preferred Pinching, EMG-based gestures performed comparably and demonstrated potential as an alternative to camera-based confirmation techniques. Chapter 13 summarizes and concludes Part III.

Finally, in Part IV, this thesis is concluded (Chapter 14) and an outlook on possible future work is presented (Chapter 15).

1.4 Publications and Preprints

This dissertation is based on several publications that have been published in peer-reviewed national and international venues and journals or are available as preprints. The original publications were partly rephrased. Additionally, I authored and co-authored papers that are outside the scope of this dissertation, which will also be listed in this section, that might be cited within the dissertation. Works marked with are based on bachelor's and master's theses I have supervised, where I was primarily responsible for the essential aspects of the final contribution, particularly regarding the experimental design, evaluation, and manuscript preparation[7].

1.4.1 Main Authorship

Journal Articles

[106] J. Hartfill*, F. Bormann*, K. Riebandt, S. Kühn, and F. Steinicke. "Objective agency measurement of different hand appearances in virtual reality with intentional binding". In: *Virtual Reality* 29.14 (2024). ISSN: 1434-9957. DOI: 10.1007/s10055-024-01085-x [8]

[110] J. Hartfill, S. Hajahmadi, S. Schmidt, G. Marfia, and F. Steinicke. "Embracing differences in virtual reality: inclusive user-centered design of bimanual interaction techniques". In: *Frontiers in Virtual Reality* Volume 6 (2025). ISSN: 2673-4192. DOI: 10.3389/frvir.2025.1586875

Conference Papers

[108] J. Hartfill, J. Gabel, L. Kruse, S. Schmidt, K. Riebandt, S. Kühn, and F. Steinicke. "Analysis of Detection Thresholds for Hand Redirection during Mid-Air Interactions in Virtual Reality". In: VRST '21: Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology. Osaka, Japan: Association for Computing Machinery, 2021. ISBN: 9781450390927. DOI: 10.1145/3489849.3489866 (Honorable Mention for Best Paper Award)

[112] J. Hartfill, M. Schrader, and F. Steinicke. "Investigating the Impact of Virtual Hand Realism on Embodiment and Redirection Sensitivity in Virtual Reality". In: *GI VR / AR Workshop*. Gesellschaft für Informatik e.V.. Germany, 2024. DOI: 10.18420/vrar2024_0016

[105] J. Hartfill, M. Arz, and F. Steinicke. "EMG-based Confirmation of Gaze Selection in Extended Reality". In: *Proceedings of the Mensch Und Computer 2025*. MuC '25. New York, NY, USA: Association for Computing Machinery, 2025, 375–384. ISBN: 9798400715822. DOI: 10.1145/3743049.3743062. URL: https://doi.org/10.1145/3743049.3743062 (Accepted for publication)

1.4.2 Preprints

These preprints are not peer-reviewed.

[7] Special thanks to Frederico Bormann, Mats Schrader, and Michael Arz. And a very special thanks to Bado Völckers, who helped build the hand scanner.

[8] The authors marked with * contributed equally to this work.

[107] J. Hartfill, F. Bormann, E. Wolf, and F. Steinicke. *The Influence of Avatar Visual Fidelity on Embodiment and User Experience in Virtual Reality*. 2025-07. DOI: 10.25592/uhhfdm.17711

[111] J. Hartfill, T. Rolff, L. Kruse, S. Schmidt, and F. Steinicke. *Realism at Hand: A Fast and Easy Pipeline for Generating Fully Articulated Photorealistic Virtual Hands*. 2025. DOI: 10.25592/uhhfdm.17705

1.4.3 Additional Contributions

These works I authored and co-authored are peer-reviewed publications that are not part of this dissertation.

[109] J. Hartfill, J. Gabel, D. Neves-Coelho, D. Vogel, F. Räthel, S. Tiede, O. Ariza, and F. Steinicke. "Word saber: an effective and fun VR vocabulary learning game". In: *Proceedings of Mensch Und Computer 2020*. MuC 2020. Magdeburg, Germany: Association for Computing Machinery, 2020, 145–154. ISBN: 9781450375405. DOI: 10.1145/3404983.3405517 (Best Paper Award)

[129] Y. Jonetzko, J. Hartfill, N. Fiedler, F. Zhong, F. Steinicke, and J. Zhang. "Evaluating Visual and Auditory Substitution of Tactile Feedback During Mixed Reality Teleoperation". In: *Cognitive Computation and Systems. ICCCS 2022*. Vol. 1732. Communications in Computer and Information Science. Singapore: Springer, 2023. DOI: 10.1007/978-981-99-2789-0_28

2

Fundamentals

2.1 Reality-Virtuality Continuum

In 1994, Milgram and Kishino [182] described the Reality-Virtuality Continuum, a scale ranging from complete reality (Real Environment, see Figure 2.1) to a complete Virtual Environment (VE). They mark two important levels on that scale: *Augmented Reality* (AR), where reality is enriched with virtual content, and *Augmented Virtuality* (AV), describing a virtual world that contains real elements. Everything on that scale except both extremes is considered *Mixed Reality* (MR). Additionally, the concept of *Extended Reality* can be added to that continuum, including everything from AR to VE. In their work, they also suggest a taxonomy of MR on three dimensions: *Extent of World Knowledge* (EWK), *Reproduction Fidelity* (RF), and *Extent of Presence Metaphor* (EPM). EWK refers to the degree to which the real world is modeled inside the computer, whether it is visualized or communicated in any other way to the user or not. The other two dimensions, RF and EPM, describe the level of realism that the used display technology is capable of. RF refers to the level of visual detail of the displayed object, ranging from simple wireframes to real-time hi-fidelity 3D animation. EPM describes the level to which the user feels like watching a screen to a visual impression that would be indistinguishable from the real world.

2.1.1 Presence, Social Presence, and Co-presence

According to Slater, presence refers to the feeling of being in a place despite knowing one is not physically there [236]. The effect is influenced by the technical capabilities of the used system, such as setups that resemble real-world impressions more closely, like displays with a large field of view (FOV), a high resolution, or head tracking to adjust the virtual field of view accordingly, as in HMDs. However, presence can also occur when watching a 2D movie. Slater [236] distinguishes two types of presence: (i) place illusion and (ii) plausibility illusion. Place illusion refers to the feeling of being in a specific place, despite knowing where one actually is. It can occur without a virtual body, i.e., in a 3D movie; however, being embodied in a virtual avatar (cf. Section 2.2) enhances sensations that resemble the real world, increasing the place illusion [223, 236]. The plausibility

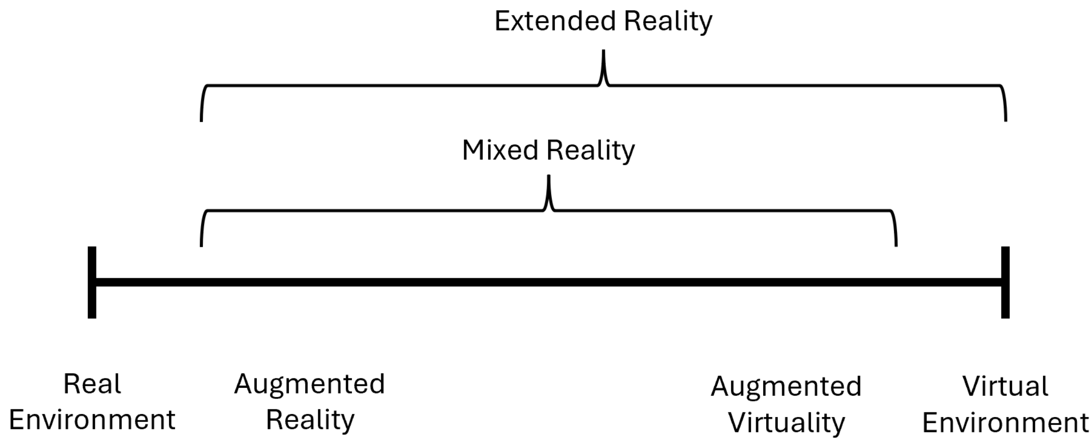

Figure 2.1: The Reality-Virtuality Continuum, adapted after Milgram et al. [182] and extended to include Extended Reality (XR).

illusion describes the feeling that actions in VR are actually happening, even when being aware that the actions are only virtual [236, 238]. Therefore, users' reactions to virtual threats are often similar to their real-world reactions, such as cringing when something unexpected happens.

Avatars can also increase *co-presence*, the sense of being together and becoming "accessible, available, and subject to another" [86]. Co-presence consists of two aspects: Perceiving others and the feeling of being perceived by others [86], which, usually, without communication devices, happens face-to-face and can also be realized with virtual avatars.

Another concept of presence is social presence [233], that focusses on the perception of others and the relationship between individuals. The Media Richness Theory adds to this idea that social presence depends on the communication media used, increasing with both the extension of the covered information and its quality [49]. Moreover, it has been suggested that intimacy increases with subtle communication cues such as eye contact, physical proximity, and the amount of smiling [9]. In that sense, immersive VR systems are a powerful communication tool, as they not only provide a high-quality sensual impression, but some devices can also capture eye gaze and smiles. Additionally, avatars make it easy to judge the interpersonal distance.

2.1.2 Virtual Environments

VEs are computer simulations that enable the user to interact within a synthetic world in real-time [34]. A VE can be used with different display types, ranging from mobile devices like smartphones and tablets to specialized VR HMDs that provide a more immersive experience. This thesis focuses on immersive setups, especially VR but also AR, that provide a high-end graphical impression and offer different input methods.

2.2 Virtual Avatars

Bailenson and Blascovich [16] define virtual avatars as "digital representations" of a human. The user steers the action of the avatar, which distinguishes it from a virtual agent, which is controlled by software. Thus, an avatar can be considered a digital replacement of the physical body. However, many aspects of the avatars' behavior might differ between the users in the real world and their digital representation. For instance, current VR technology usually does not capture all aspects of body movement, such as leg movements or facial expressions. This missing information can be computationally replaced, resulting in some form of a hybrid agent-avatar [148]. Virtual avatars are usually perceived from a first-person perspective to increase the SoE towards the avatar, but using a third-person perspective can be beneficial for space awareness [93]. Users tend to adapt their behavior and attitude to the appearance of their virtual avatar, known as the Proteus effect [100, 115, 217, 230, 239, 277, 278]. This concept is assumed to be based on social cognition theory, as people try to act in a way others expect them to, or what they think others expect [172]. Regarding implicit racial bias, embodying a dark-skinned avatar has been shown to decrease implicit racial bias toward dark-skinned people [171, 198]. Also, this effect has been shown to persist even a week later [19]. So, the visual representation plays a crucial role when designing immersive embodiment experiences, especially when they are intended to match reality.

2.2.1 Avatar Visual Fidelity

The visual impression of an avatar is referred to as visual fidelity and can be divided into three dimensions [84, 174]: (i) anthropomorphism, (ii) realism, and (iii) truthfulness.

In this context, anthropomorphism relates to the layout of the virtual body, the amount, position, and DoFs of its limbs, ranging from humanoid to non-humanoid in terms of structure and motion range. A humanoid avatar makes it easier for the user to integrate the virtual body into the user's body schema. Layouts diverging from the user's body schema are possible, as it is adaptable due to homuncular flexibility [272]. It has been shown that it is possible to control different body layouts in VR, like prolonged arms [137], tails [246], additional or fewer fingers [120, 228], or different hand sizes [114].

Realism describes the style of how virtual objects and environments are visualized [94, 177] and can range from abstract and cartoonish to photorealistic. The maximum level of detail is limited by the computing power and display technology. Zell et al. [283] found that the shape is the key dimension for perceived realism, as it directly interacts with anthropomorphism. An extreme example of this would be visualizing a hand with a single square pixel, which would make it hard without context to recognize it at all or use it intuitively. Regarding avatars, Fleming et al. [73] found that improvements in render quality had no significant impact on appeal ratings of a virtual avatar.

The truthfulness of a virtual object or avatar characterizes how close it is designed regarding its real-world counterpart, ranging from a generic representation, like choosing an avatar from a set of predefined avatars, to personalized, where the avatar would be fitted according to the user. When confronted with a virtual avatar that resembles the self, users are willing to get closer to such a self-avatar than they would with an avatar that is considered someone else [15], just like approaching their own reflection in the mirror. Moreover, there is evidence that users are more engaged when using a truthful avatar and also prefer such an avatar over a generic one [163]. Waltemate et al. [264] showed that personalized avatars can increase presence compared to generic avatars.

2.2.2 Sense of Embodiment

Sense of Embodiment (SoE or embodiment) describes the feeling that an object (virtual or real) belongs to or replaces one's own body or parts of it. Kilteni et al. [136] define SoE toward a body B as "the sense that emerges when B's properties are processed as if they were the properties of one's own biological body." The state of one's own body can be perceived through different sensory channels: Visually, but also through spatial orientation by the vestibular system, proprioception, touch perception as well as the perception of temperature and pain. These channels are not processed separately in the brain but are rather integrated to build a reliable perception of the body and environment, known as multisensory integration [243]. The rubber hand illusion, which is based on a tactile and visual impression of a fake limb, was first described by Botvinick et al. [29]. They showed that it is possible to induce a feeling of disembodying one's own arm and instead embodying a rubber arm by providing a synchronous visuo-tactile impression on both the real and the fake arm. SoE over a virtual body is fostered when the artificial stimuli fit the perceived stimuli, as it makes multisensory integration easier. It has been shown to be linked to several factors [97], such as the avatar's appearance [10, 66, 164, 165, 167, 253, 254, 264], its control [66, 265], as well as the viewpoint [10, 28, 60, 137, 154, 155, 201]. However, also the locus of control (the degree to which people believe that they have control over the outcome of events or attribute them to external factors) [50, 127], as well as user preference [35, 79], emotion [77], vestibular signals [27, 28, 137, 161] and visuo-tactile stimuli [10, 29, 137, 143, 155, 191, 235] play a role in SoE.

Regarding virtual avatars in immersive VR setups, Kilteni et al. [136] suggest SoE is based on three components: (i) *Sense of Self-Location* (SSL), (ii) *Sense of Ownership* (SoO or ownership), and (iii) *Sense of Agency* (SoA or agency).

Sense of Self-Location: The experience of being inside a body and the perception of the spatial volume of that body is referred to as SSL [136]. Usually, one feels located inside their own physical body; however, out-of-body illusions are also a topic of research [27]. SSL is based on visuospatial perspective (first-person perspective (1PP) or third-person perspective (3PP)), vestibular signals, and tactile input [136]. Although we usually experience a 1PP in our body, it is possible to induce SSL from a 3PP [28, 154, 155]. However, the effect of SSL is stronger for first-person experiences. It could be shown that when a virtual body is exposed to a threat, the physical reaction is stronger for 1PP than for 3PP [10, 200, 201].

Sense of Ownership: When a body is attributed to the self, this evokes SoO towards that body or body parts [83]. That body then is perceived to be the source of the sensations. Both top-down and bottom-up processes influence SoO [253, 254]. Regarding bottom-up influences, both spatial and temporal synchrony are important, such as temporal integration of visual and tactile information, as in the rubber hand illusion (RHI) [29, 253]. Furthermore, visuo-proprioceptive synchrony was also found to enhance SoO [56, 253]. For top-down influences, the similarity of the virtual body in terms of anthropomorphism [10] or configuration [46, 61, 253] has been shown to be critical.

Sense of Agency: While SoO can be experienced over a static body, SoA refers to the sense of having "global motor control, including the subjective experience of action, control, intention, motor selection, and the conscious experience of will" [28]. SoA also depends on visuo-motor synchronicity and has been suggested to be linked to the correlation of the predicted sensory outcome of an action (efference copy) and its actual sensory outcome [136, 225, 268]. This effect appears to be independent of the consequences of the action but rather limited to the sensory feedback of the action [225].

2.2.3 Virtual Hand and Embodiment

Argelaguet et al. [8] investigated the effect of virtual hand appearance on SoA and SoO in VR. While they found increased SoO with a higher realism level, the effect on SoA was decreased. The tested hand models (abstract, iconic, and realistic virtual hands; see Figure 2.2) were controlled using handtracking technology.

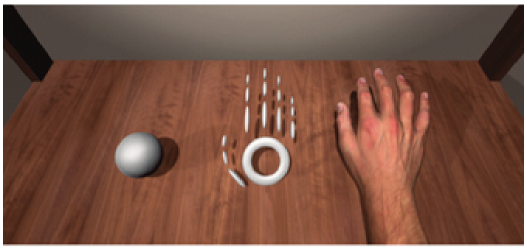

Figure 2.2: Abstract, iconic, and realistic virtual hands (from left to right) used by Argelaguet et al. [8]. © 2016 IEEE, adapted

Lin and Jörg [157] investigated the virtual hand illusion with six different hand models. Five of them had an anthropomorphic layout with five fingers but different appearances, from realistic to robotic, and one was a wooden block hand. All hands were controlled using hand tracking. They found the anthropomorphic model to lead to a stronger effect of virtual hand illusion, with the realistic hand having the strongest effect. No effect of appearance on SoA was found.

Ogawa et al. [193] investigated whether object size perception in VR depends on hand representation. Participants embodied realistic, iconic, and abstract virtual hands (see

Figure 2.3), which were adjusted to their hand size. Additionally, the realistic hand models matched the participant's gender. The hand was controlled using leap motion hand tracking. The three sub-scales of the embodiment questionnaire used (*Ownership*, *Agency*, and *Location*) each revealed a significant effect for hand realism, with realistic and iconic having significantly higher ratings than abstract.

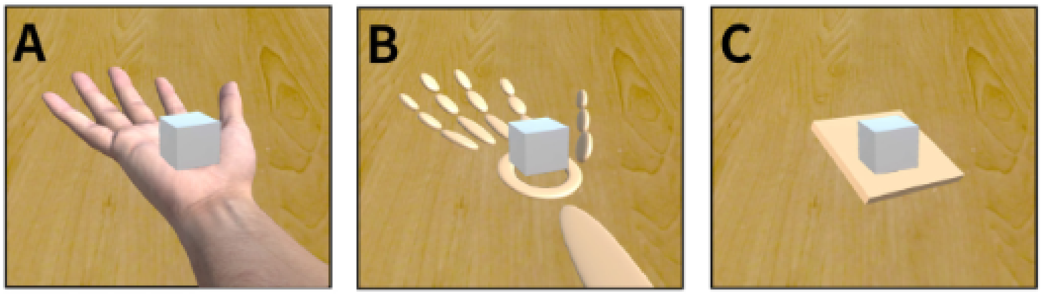

Figure 2.3: Highly realistic (A), iconic (B), and abstract virtual hands (C) used by Ogawa et al. [193]. © 2019 IEEE, adapted.

Zhang et al. [287] investigated the effect of hand appearance on the feeling of embodiment and presence. Participants played a VR puzzle game with 5 different virtual hand representations, ranging from static objects to a more realistic hand representation (Block, Cursor, Iconic hand, Robot hand, Realistic hand; see Figure 2.4). The virtual hand was controlled using the VR controller. They could show a significant effect of hand realism level on presence and SoO. For SoA, no significant effect could be found. Pairwise comparison revealed significant effects only between unarticulated hands (Block or Cursor) and anthropomorphic hands (Iconic, Robotic, or Realistic) for both presence and SoO.

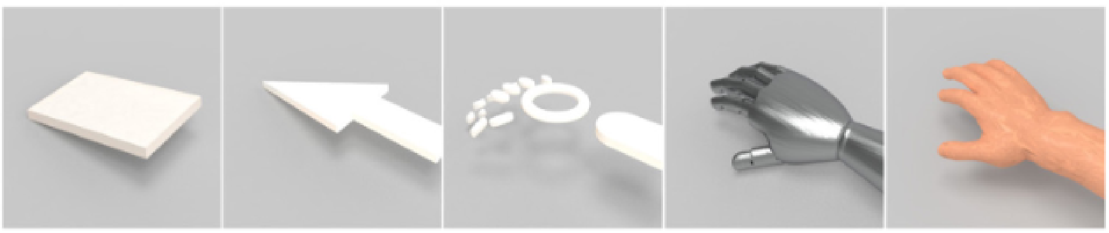

Figure 2.4: Block hand, Cursor hand, Iconic hand, Robotic hand and, Realistic hand (from left to right) used by Zhang et al. [287]. © 2020 IEEE

Heinrich et al. [113] investigated hand appearance, including personalized hands in VR and AR. Using four levels of hand appearance (Wood hand, Wobotic hand, Realistic hand, and Augmented Virtuality hand with personal texture; see Figure 2.5) that were controlled using hand tracking, they could not find a significant effect of hand appearance on SoA or SoO.

Quite recently, Zhang et al. [286] investigated the effect of hand appearance on embodiment using different measures, including eye tracking. Using five different hand models with different degrees of freedom for embodiment, they found decreased ratings for SoO,

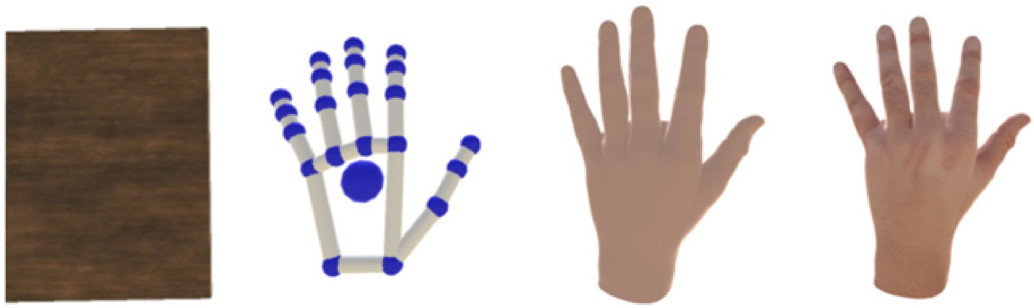

Figure 2.5: Wood hand, Robot hand, Realistic hand and Augmented Virtuality hand with personal texture (from left to right), used by Heinrich et al. [113]. © 2020 Springer-Verlag London Ltd.

SoA, and overall embodiment for the block hand over the other four fully articulated hand models with a questionnaire. Using the IB paradigm based on time estimation, no effect of hand appearance on SoA could be found. Regarding the significant differences for the block hand, the authors suggest this to be related to the level of degrees of freedom between the hand models. Moreover, they suggest that the way of controlling the virtual hand could influence the feeling of embodiment towards the hand. While these works all

Figure 2.6: Block hand, Minimal hand, Capsule hand, Low-poly hand, and Human hand (from left to right) used by Zhang et al. [286]. © The Author(s), 2023.[1]

include hand models with several levels of realism (up to four levels of realism for fully articulated hands in [286]), the number of DoFs, an essential part of anthropomorphism, only appears in two levels: fully articulated hand and completely unarticulated hand (block, sphere, and cursor).

2.2.4 Virtual Hand Redirection

Novel interaction concepts utilize visual dominance to improve interactions in VEs, in particular, by redirecting the users' hands to real-world proxy objects to provide haptic feedback. Such interaction techniques, including redirected touching and haptic retargeting, introduce a discrepancy between the virtual and real hands [144]. Researchers have started exploring these intentional manipulations in the context of different application areas, for example, for the training of pilots [144] and surgeons [242]. Further application fields with enormous potential for redirection techniques are therapy and rehabilitation.

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For instance, when decelerating the movement of virtual hands, users would have to perform larger motions in the real world. In the context of redirected walking, it was already shown that such manipulation strategies can reduce gait asymmetries [125].

Since detectable hand redirections could lead to decreased task performance or, at least, peculiar sensations [144], detection thresholds are of particular interest for such manipulations in the therapy context. Unnoticeable hand redirections might be useful for conventional physiotherapy exercises or other therapies involving movements of the upper limbs, like mirror therapy [210]. If exercises are not performed correctly, participants could be unnoticeably redirected. Especially with decelerated virtual hands, users could be animated to perform larger movements than they are aware of. This can be used in the context of chronic pain therapy, where some patients experience fear of pain and therefore avoid movements that are mistakenly anticipated to be painful [48, 262]. As patients do not get visual feedback of their hands' real positions, fear of pain could be reduced. Moreover, it was shown that identifying with a virtual body can have an analgesic effect [121, 160], highlighting the importance of the virtual hand appearance. So even without fear of pain, therapeutic outcomes might be improved as exercises are more intense due to slightly larger real hand movements.

2.3 Research Methods

To evaluate the different aspects that contribute to a convincing virtual body illusion, several data acquisition methods were used, covering both quantitative measures, such as efficiency, error rate, and qualitative measures. This section gives an overview of the research methods used in this thesis, covering user-centered design, interviews types, and presents used standard questionnaires.

2.3.1 User-Centered Design

User-centered design (UCD) is a design approach that focuses on the inclusion of the users through the whole process to ensure a high level of usability of the final product [95, 232]. It is based on three principles: Early focus on users and tasks, where designers should get to know the potential users as well as the tasks; empirical measurement of user feedback for early prototypes as well as iterative design, where potential issues with the prototypes can be recognized and approached [95]. The design phases are described according to Gould and Lewis [95]: In the initial design phase, this includes collecting information about the users and the environment that should be approached. Then, in the iterative development phase, a prototype should be designed in a way that it can easily be adapted. Then users should try the prototype and provide feedback, which can then be incorporated into the next iteration of the design prototype.

UCD was used in Chapter 11 when investigating novel input techniques for HMDs. In the initial phase, we conducted a semi-structured interview with a person with unilateral limb differences to learn about his experience with PCs and gaming consoles and his requirements for input mechanics for HMDs like the Quest 2. Based on that, we developed 3 prototypes with varying levels of responsibility for the secondary hand and evaluated them in two ways: Firstly with students and secondly with 4 participants with unilateral limb differences or motion restrictions of the upper limbs. Here again, we conducted semi-structured interviews that further investigated the possible usage of the prototypes in everyday life and the users' ideas for visualization of the input mechanics in the VE.

2.3.2 Interview Types

One way to collect information in the initial design phase is interviews. According to Fontana and Frey [74], interviews can be classified into three main types: (i) unstructured, (ii) structured, and (iii) semi-structured. There are also group interviews that can follow these types of interviews. The interview types will be described in the following according to Sharp et al. [232].

In structured interviews, the questions are predefined and standardized across participants, like in a questionnaire. Usually, this style contains closed questions, meaning that all possible answers are known ("What do you like better, A or B?"). This type of interview is useful when the topic is narrow.

An unstructured interview, on the other hand, is a conversation that intends to get insight into a specific topic. The questions are open so that the interviewee is animated to answer in detail. The conversation does not have a predefined direction but can be adapted throughout the process. The data generated from such interviews can be rich and complex, providing insights into complex and unexpected aspects of the topic.

A hybrid form of both the aforementioned types is called semi-structured interviews. Here, the interviewer usually has some predefined questions but is open to further investigating an answer if necessary.

2.3.3 Standard Questionnaires

Throughout this thesis, several standard questionnaires were assessed that allow to compare results across different works. These questionnaires cover more general topics like usability, task load, simulator sickness, and user experience. Some are more specifically for SoE, SoA or assessing the uncanny valley, self-assessment, or the handedness of the user.

System Usability Scale The usability of a system can be defined as how "appropriate to a purpose" the design is [130]. According to ISO 9241-11 [64], the following aspects should be covered when measuring usability: effectiveness (*Is it possible to complete the task?*), efficiency (*How many resources are necessary to complete the task?*), and satisfaction (*How do the users react to the system?*). This can be evaluated using the System Usability Scale (SUS) [130]. It consists of 10 questionnaire items that users answer on a 5-point Likert scale from 1-Strongly disagree to 5-Strongly agree. It is administered directly after using the system and should be answered intuitively, without thinking about the items for a long time. The score is calculated by first calculating the score contribution for each item (Scale answer position minus 1 for questions 1, 3, 5, 7, and 9 and scale answer position minus 5 for items 2, 4, 6, 8, and 10) and adding up the score contributions, such that the final score will be in the range between 0 and 100. A mean SUS of 50.9 (SD 13.8) was determined to be OK in terms of system usability, while scores of 71.4 (SD 11.6) can be considered good and scores of 35.7 (SD 12.6) as poor usability [20]. The SUS was used to assess usability in Chapters 4 and 11.

NASA Task Load Index Subjective workload, or task load, describes "the cost incurred by a human operator to achieve a particular level of performance" and includes factors such as the requirement of a task itself and the operator (skills, behavior, and perception), but also includes factors regarding the circumstances under which the task is performed [103]. It can be assessed with the NASA Task Load Index (NASA TLX) [103], which consists of six rating scales: *Mental demand*, *Physical Demand*, *Temporal Demand*, *Performance*, *Effort* and *Frustration Level*, which are answered on a scale from 0 to 100 in steps of 5. While the authors originally proposed an additional weighting step between the rating scales, using the raw form without the weighting has been established in the field of HCI. Task load was assessed with the NASA TLX in Chapters 4, 10 and 11.

Simulator Sickness Questionnaire Simulator sickness, or cybersickness, can include various symptoms such as eye strain, headache, pallor, sweating, dryness of mouth, fullness of stomach, disorientation, vertigo, ataxia, nausea, and vomiting [150]. These symptoms can occur during the exposure to VE and can also persist for some time. The effect is based on sensory conflict that can arise during simulations, such as the mismatch between the visual perception of the movement in VR and the perceived movement by the vestibular system [150]. The SSQ assesses these symptoms with 16 items that are answered on a 4-point Likert scale [135]. From these items, the three sub-scales *Oculomotor*, *Disorientation*, and *Nausea* can be calculated, as well as the total score. Simulator sickness was evaluated with the SSQ in Chapters 4, 5, 6 and 12.

Virtual Embodiment Questionnaire and VEQ+ Embodiment, as described in Section 2.2.2, can be measured with different questionnaires. One of them is the Virtual Embodiment Questionnaire (VEQ) with 12 items, divided into 3 sub-scales: *Ownership*, *Agency*, and *Change* [218]. While *Ownership* and *Agency* directly relate to SoO and SoA, as proposed by [137], cf. Section 2.2.2, *Change* refers to the perceived change in the body schema. Participants answer on a scale from 1 to 7. This questionnaire was extended by [71] (VEQ+) by 12 additional items, 4 for each of the sub-scales *Self-location*, *Self-attribution*, and *Self-similarity*. These questionnaires were used in Chapter 10.

Avatar Embodiment Questionnaire Another questionnaire for SoE is the Avatar Embodiment Questionnaire (AEQ) [197]. It consists of four sub-scales that do not directly relate to the embodiment subcomponents described in [137]. It consists of 16 items, of which some contribute to several of the subscores: *Appearance*, *Response*, *Ownership* and *Multi-Sensory*. This questionnaire was used in Chapters 6 and 10.

Uncanny Valley Index The uncanny valley, originally published in 1970 [185], describes the drop in emotional appraisal for objects that are close to human appearance. While affinity generally increases with increasing human likeness, the curve suddenly forms a U-shape before reaching perfect human appearance, see Figure 2.7, resulting in feelings described as cold and eerie [117].

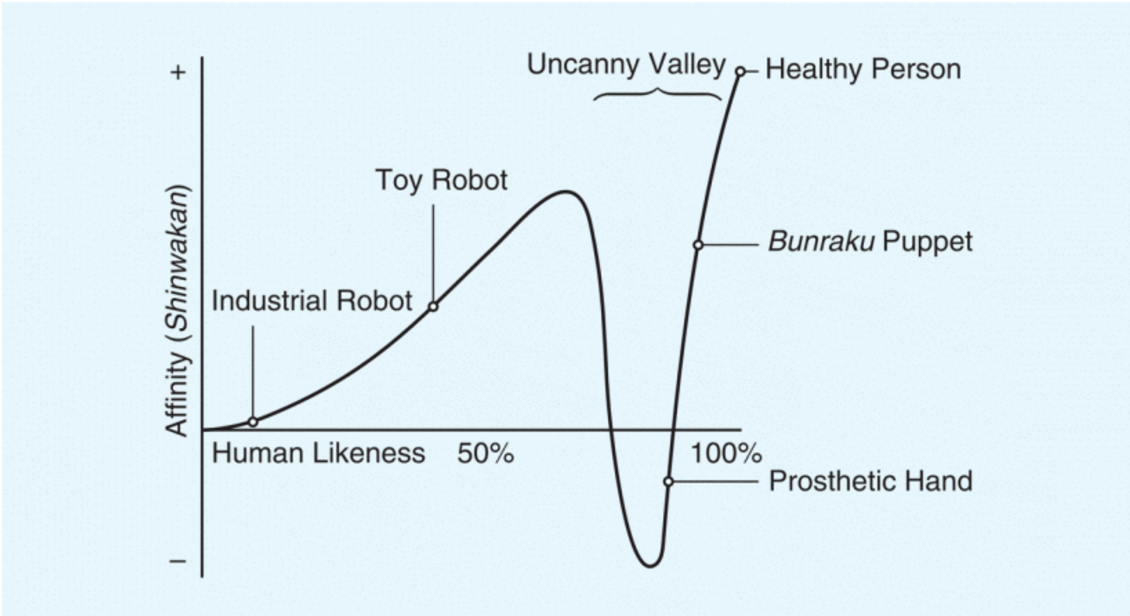


Figure 2.7: The relationship of human likeness and affinity, showing a large drop in affinity close to the human likeness of a healthy person [185]. ©2012 IEEE.

This effect can be measured using the Uncanny Valley Index (UVI) [117]. The questionnaire consists of 18 adjacent adjective pairs, divided into the sub-scales *Humanness*, *Attractiveness*, and *Eeriness*, which participants answer on a 7-point scale from -3 to 3. The UVI was used in Chapter 10.

Self-Assessment Manikin The Self-Assessment Manikin (SAM) is a measure for perceived pleasure, arousal, and dominance for various stimuli [30] on a visual scale. It was validated and adapted from a five- to a nine-point scale by Bruun and You [33]. SAM was utilized in Chapter 10.

Edinburgh Handedness Inventory To assess hand dominance, one of the mainly used tools is the Edinburgh Handedness Inventory (EHI) [194], which assesses which hand people usually use to perform specific everyday tasks. Veale et al. [259] developed a short form of the EHI, consisting of 4 items, and expanded the answer scale to a 5-point scale, ranging from "always right" to "always left." The short form of EHI was used in Chapters 5 and 11.

Part II

Virtual Hands: Appearance and Redirection

3 Introduction to Virtual Hands

In recent years, VR has gained increasing relevance since HMDs have become more and more affordable. This trend opens up the question of which factors influence the immersive experience inside VR. Virtual hands are of special interest for this, as they are important for manipulating objects in the environment and supporting communication with others. Moreover, this body part is frequently in the user's field of view, which makes the visual appearance and behavior of virtual hands important to create a convincing virtual hand illusion. Part II of this work investigates ***RQ1****: How do hand appearance and hand redirection contribute to the virtual hand illusion?* RQ1 is divided into three research questions that are introduced in the following.

RQ1.1: Does virtual hand realism influence Sense of Agency? Hand realism affects SoO [8, 132, 133, 146, 157, 162, 193, 287]. Regarding SoA, another important dimension of SoE, several studies did not find a significant effect of hand appearance [8, 133, 146, 157, 162, 193, 287]. However, Ogawa et al. found SoA to be positively related to virtual hand realism [193]. In their study on object size perception, Ogawa et al. investigated SoE, including SoA, towards three virtual hand models (highly realistic, iconic, and abstract), illustrated in Figure 2.3. They found significantly higher ratings for SoA for the realistic and iconic hand, which has an anthropomorphic layout and is fully articulated, over the abstract representation, which was an unanimated block. No significant difference between the first two could be found.

All these studies on the effect of virtual hand appearance measure SoA using some form of questionnaire. As the focus of these works is more on SoE, not necessarily on SoA, the number of questionnaire items is rather low, ranging from a single item [133, 157], over three items [162], four items [193, 287], or up to six items [8, 146]. In the study by Argelaguet et al. [8] concerning differences in the SoE for different hand representations, participants were asked to perform Pick-and-Place tasks and obstacle avoidance tasks with different virtual hands. In their VR setup, they compared hand models with different levels of abstraction (realistic, iconic, and abstract) and varying behavior. Their data did not support their hypothesis of SoA being increased in the realistic virtual hand condition.

Of the six items for SoA, two did not reveal significant differences, while two showed significantly lower SoA scores to at least one other hand model, and the remaining two showed higher SoA scores for the realistic hand over at least one other hand model. This suggests that questionnaires for SoA might not be capable of reliably measuring SoA, especially when very few items are used. This is in line with findings from You et al. [280], who investigated two different questionnaires for SoA when users embodied avatars with different levels of control over the avatar. Both questionnaires did not show a significant effect of control level on SoA. They conclude that measures for SoA should be evaluated.

In the field of neuroscience, however, an objective measure for SoA is established: the intentional binding (IB) paradigm. It is based on the time estimation of an action, followed by its outcome [98] and has already been shown to be applicable in VR setups in other contexts [145, 168].

We further investigate whether the effect of hand appearance on SoA can also be found in virtual hands with the same anthropomorphism level (fully articulated hands) but different realism levels (blue semi-transparent and natural) by using an objective measure, the IB paradigm. Our results indicate that SoA was elicited towards both hand models, but no significant effect for hand realism could be found. However, as Ogawa et al. [193] reported significant effects only between hand models with varying DoFs, anthropomorphism appears to be the crucial factor to elicit SoA, not realism.

RQ1.2: Do motion direction and handedness influence redirection sensitivity? Changing the mapping between the hand motion and the visualized pose in VR, leading to visual-proprioceptive discrepancies, is called (hand) redirection or retargeting. If such manipulations are small enough, they can stay unnoticed by the user [39, 192]. One of the first works in this field was introduced by Burns et al. [36]. They identified detection thresholds for gradually increasing angular offsets between real and virtual hands. These findings have been derived in a distracting game context, and, therefore, the transferability to other scenarios remains unclear. Recently, more formal psychophysical approaches are used with trial-wise constant stimuli, where users focus on identifying the discrepancies without induced distractions. For example, Lee et al. [153] analyzed the sensitivity regarding errors in finger tracking and found that users tolerate discrepancies of about 5 cm.

In the context of hand redirection, Zenner and Krüger [284] studied hand redirection in a reaching setup with angular and gain-based hand warping (accelerated as well as decelerated movements) under different user distraction scenarios. An influence of distraction level on detection threshold could not be found. The proposed redirection method is well applicable for reaching and pointing motions but is hardly transferable to more complex interactions in 3D space, such as moving an object to a different position or adjusting a slider. The virtual hand was not connected to an avatar, and the hand was not articulated, but the participants' fingers were fixed to the pose of the virtual fingers, possibly limiting the applicability of the results to setups with fully articulated virtual hands or whole-body avatars. Also, the fit between the real and virtual hand could not be adjusted, as only two types of hands (smaller for females and larger for males) were used.

Esmaeili et al. [65] conducted two experiments to determine detection thresholds depending on spatial axis and task complexity. They implemented a gain-based hand redirection method similar to the gain warping by Zenner and Krüger for accelerated as well as decelerated movements. In their first experiment, participants were asked to freely move their hands and decide whether the motion was natural or not, while it was redirected on one spatial axis. The authors derived detection thresholds for all three spatial axes and found that the detection thresholds differ significantly between the axes. In the experiments, the Oculus Touch Controller was used, which provides a simple form of hand and finger tracking. The virtual hands were not connected to an avatar, nor was the hand size adjusted, possibly limiting the applicability of the results to setups with other configurations, such as hand tracking. However, whether redirection sensitivity differs between specific motion directions, such as between both directions on each axis, remains unclear. Also, in these studies only one hand was investigated. So whether the reported detection thresholds apply to both hands remains an open question. Understanding redirection sensitivity well is important in different contexts, such as for hand redirection in games, to not interrupt the immersion of the game, or in medical contexts, such as rehabilitation exercises, where patients should not be aware of their actual hand motion.

In Chapter 5 we further investigate redirection sensitivity with a hand retargeting method for decelerated hand movements. With this technique, users need to perform larger movements to reach for an object in the VE, which can be utilized, for example, in therapeutic applications. In a psychophysical experiment, we analyzed detection thresholds for six different motion paths in midair for both hands. We found significantly different detection thresholds between movement directions on each spatial axis, informing researchers and designers of immersive VR experiences better about the principles of redirected hand motions. For handedness, no effect on redirection sensitivity could be shown. To verify our findings, we applied the identified gains in a playful application in a confirmatory study.

RQ1.3: Does embodiment influence redirection sensitivity? To further investigate the fundamentals of a convincing virtual hand illusion, we investigated whether there is a connection between SoE and redirection sensitivity. SoE, especially SoA, has been shown to be linked to motor synchrony and colocation [25, 75, 225]. Also, the self-avatar follower effect [89] shows the interplay between the position of the virtual limb and the actual arm position. However, if there is a direct connection between SoE and redirection sensitivity, it has not been investigated yet, to the best of our knowledge. As the effect of virtual hand appearance on SoE [10, 66, 164, 165, 167, 253, 254, 264] has been shown, we investigate the effect of SoE on redirection sensitivity by equipping users with virtual hands with different appearances, varying in anthropomorphism and realism.

Ogawa et al. [192] investigate detection thresholds for remapped reaching movements and the effects of hand realism. In their setup, participants reached a target with their right hand while the virtual hand was shifted towards one side so that the real hand had to be moved to the opposite side for compensation. They found a higher sensitivity for inward shifts (virtual right hand redirected to the left, actual right hand moves to the right) compared to outward shifts for the abstract hand representation (Sphere). For the realistic hand representation, no differences in sensitivity could be found. The authors used hand tracking as an input technique. However, in the Sphere condition, where the difference in redirection sensitivity was observed, the sphere was only attached to the index finger. Whether this effect can also be found between more anthropomorphic hand models and in different redirection scenarios, such as gain-based redirection and motions other than pointing, remains unclear.

As in Chapter 5 we found significant differences between motion direction, and the connection between avatar appearance on SoO has been shown [8, 132, 133, 146, 157, 162, 193, 287], we further investigate the interplay between SoE and redirection sensitivity, depending on avatar appearance: Does a higher identification with the virtual body due to a closer resemblence of a real body influence the user's expectation towards the motion of a virtual body, making people more sensible to diversions between the real and virtual body? In our study, we investigate a gain-based redirection method for horizontal movements. Hand appearance was tested for four different hand models with varying DoFs and degrees of realism. Our results did not reveal an effect of hand appearance with varying levels of realism and anthropomorphism on redirectionsensitivity for a gain-based redirection on a horizontal axis, suggesting that redirection sensitivity is independent of hand appearance in such a scenario. However, we found a significant effect on SoE, with the two more anthropomorphic hand models eliciting higher levels of SoE than the two hand models with limited DoFs and, thus, a lower anthropomorphism, underlining the importance of fully articulated hands on SoE. Taken together, SoE does not seem to influence detection thresholds for hand redirections.

Photorealistic Virtual Hand Models In this part we presented two studies with varying hand realism. However, the visual fidelity of these hands was not photorealistic. For future works, it would be interesting to see whether our findings of hand realism in SoA (Chapter 4) and SoE (Chapter 6) also apply to photorealism. While different approaches for generating such hand models have been proposed [184, 187], several additional steps are necessary until such 3D meshes can be used as fully articulated virtual hands in VR: First they need to be rigged, meaning the mesh needs to be supplemented by a construct of bones or joints called a rig that determines the way the object can move, comparable to a skeleton in mammals. In Chapter 7 we present a fast and easy pipeline from taking the initial dataset, over reconstructing the 3D mesh, and rigging it, until importing the final hand model in a Unity scene and setting up the hand tracking support. We provide open-source software recommendations and guidelines for setting up photorealistic personalized virtual hands within 30 minutes.

4 Investigating the Effect of Virtual Hand Realism on Agency Using Intentional Binding

Figure 4.1: SoA can be objectively measured using the IB paradigm with the Libet clock (left). Participants' time judgment of a tone that appears at time 10 is quite accurate (light red point). When asked to press a button first (time 0, white point) with one of the virtual hands (middle and right), time judgment of the tone at time 10 shifts towards the action (red point).

In this work, we use the IB paradigm to further investigate the effect of avatar hand appearance on SoA over fully articulated virtual hands with two levels of visual realism: natural hands and semi-transparent blue hands. This chapter investigates **RQ1.1** and is based on the following publication:

> J. Hartfill*, F. Bormann*, K. Riebandt, S. Kühn, and F. Steinicke. "Objective agency measurement of different hand appearances in virtual reality with intentional binding". In: *Virtual Reality* 29.14 (2024). ISSN: 1434-9957. DOI: 10.1007/s10055-024-01085-x

4.1 Introduction

Recently, commercial VR HMDs, like the Oculus Quest 2 [1], Vive Focus 3 [2] and Pico Neo 3 Pro [3], support easy-to-use solutions for hand tracking without the need for additional hardware, which allows for a more natural and intuitive interaction within VR. In commercial applications and games that support hand tracking, the users' hands are often visualized quite abstractly (e.g., *Job Simulator* (cartoonish), *Unplugged* (blue semi-transparent), *Cubism* (white semi-transparent), *Waltz of the Wizard* (bluish), *Virtual Desktop* (black)) or more realistically, like in *The Climb*, *Half-Life: Alyx* or *Horizon Workrooms*. The Oculus Quest, which has a high market share, equips the user with bluish, semi-transparent hands in the home environment. While this has recently been shown to enhance object manipulation capabilities [256], the effect on embodiment remains unclear, since, to the best of our knowledge, there is no work on embodiment including semi-transparent hands.

The effect of hand realism on SoE and specifically SoA has been investigated recently, with mixed findings. However, in the field of Human-Computer Interaction, questionnaires are usually used to assess data on this question. In the field of neuroscience, the IB paradigm has been established, providing an objective measure for SoA. In this work, we use a virtual version of that paradigm to assess agency over two levels of virtual hand realism.

This work is guided by the following two research questions: **RQ1.1.1**: Does SoA differ with different appearances of a fully articulated virtual hand? **RQ1.1.2**: Do objective and subjective measures for agency yield consistent results?

This chapter is structured as follows: Section 4.2 gives an overview of related work on explicit and implicit agency measures. In Section 4.3 we present the experiment. The analysis and results are presented in Section 4.4, followed by the discussion of the findings in Section 4.5. This Chapter is concluded in Section 4.7 and an outlook on potential future work is given in Section 4.8.

4.2 Related Work on Explicit and Implicit Measures for Agency

IB, originally reported by Haggard et al. [98], describes the effect that participants perceive voluntary movements to be later in time and sensory outcomes of that action to be earlier, binding together the action and its outcome. If participants are asked to judge the timing of an event like an intentional action or a sound, the estimation usually is quite precise. When, on the other hand, they are asked to press a button, which is followed by a sound, the button press is perceived to be later in time and the timing of the sound is reported to be earlier. The left part of Figure 4.1 shows the Libet clock, which is often used in the IB paradigm. A red dot circles the clock face at a fixed speed. When participants are

[1] https://www.oculus.com/quest-2/
[2] https://www.vive.com/eu/product/vive-focus3/overview/
[3] https://www.picoxr.com/global/products/neo3-pro-eye

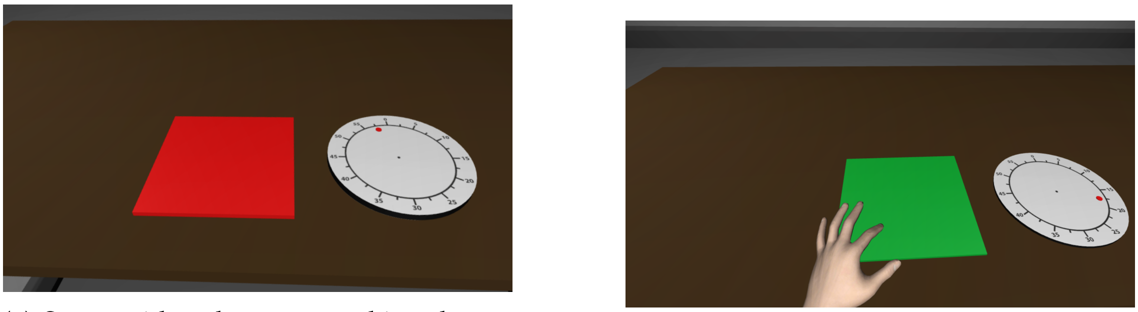
asked to judge the timing of a sound that appeared when the dot is at time 10, usually the estimation is quite accurate (light red dot). However, if participants are asked to press a button (time 0, white dot), which is followed by a sound when the dot is at 10, the tone is estimated to be earlier (light red dot). Moreover, when asked to report the timing of a random button press, the estimation usually is later than the actual action, binding together action and outcome. The paradigm has already been successfully applied in VR scenarios [145, 168].

Ma et al. investigated the relationship between implicit and explicit measures of agency and ownership in a VR setup [168]. Agency was measured implicitly using the IB paradigm, and ownership using proprioceptive drift. For both, standard ratings were used as explicit measures. The authors manipulated synchrony, type of end effector (hand vs. triangle), and spatial congruency between real and virtual hand. They found similar effect patterns for both agency measures and a strong correlation between the explicit measures and concluded that there are shared as well as non-shared information sources underlying each process. Although they manipulated the end effector level, they do not report findings on possible difference on agency over the hand or triangle version, as this was not their focus of work. SoA was assessed before and after VR exposure, where participants solved tasks either with an avatar (VR group) or without (VR control). They found a comparable binding effect size for the VR group (IB Task in VR with avatar) and reality control group (IB in reality, own body visible) but a lower IB effect size for the VR control group (IB task in VR, no avatar). Moreover, IB already occurred in the pretest, indicating no long exposure phase is necessary to elicit SoA over an avatar. Participants also rated their SoO and SoA using a questionnaire, which did not show a significant difference before and after VR exposure.

In this work, we use the IB paradigm to further investigate the effect of avatar hand appearance on SoA over a virtual avatar with fully articulated hands. For the IB paradigm, we remain closer to the originally proposed setup, as it might be more accurate than interval estimation reporting, and we include haptic feedback through a physical button. We also include a questionnaire to connect our findings to previous works.

4.3 Experiment

We conducted an experiment to analyze the effect of different hand representations on SoA using the IB paradigm. Participants were immersed in a VE with different hand representations and were asked to report time judgments for certain events. The experiment procedure was approved by the Local Psychological Ethics Committee at the medical center involved in this work.



(a) Setup with red square marking the position where the space bar of the physical keyboard was placed.

(b) Space bar is pressed which causes the square to turn green as visual feedback

Figure 4.2: Virtual experiment setup with Libet clock and button press area. The red marker is moving along the inner circle of the Libet clock with a speed of 2560 ms per rotation.

4.3.1 Setup

Participants were sitting at a desk and wearing the Oculus Quest 2, connected to a PC (Intel Core i7 6700HQ, 16 GB RAM, NVIDIA GeForce GTX 970M, Windows 10 Pro). They were immersed in a spatially aligned desk setup. The desk height adjustment was done using the controllers. For the actual experiment, only hand tracking was used, not the controllers. The size of the virtual hand was set to the participants' hand size using the Oculus SDK. On the real desk, a consumer keyboard was placed such that the space bar was inside the button area in VR, which was about 25×25 cm. The color of the button area changed to green when the space bar was pressed to provide visual feedback to the input; see Figure 4.2. Next to the button area was the clock face, with a diameter of 25 cm. Initially, the Libet clock face was empty. During times when participants were asked to monitor the timing of an event, a circular red marker rotated along the inner border of the Libet clock, finishing one rotation in 2560 ms. We evaluated two different hand representations, a realistic one and a blue semi-transparent one, see Figure 4.1, which are similar to many hand models already used in games and other VR applications. Semi-transparent hands are popular for manipulation tasks, like in *Unplugged* (blue semi-transparent) or *Cubism* (white semi-transparent), because they don't cover the manipulated object. For the second model, we chose a more natural material that resembles realistic hands, like they are used in more realistic-inspired games like *The Climb*, *Half-Life: Alyx* or *Horizon Workrooms*. For both hand realism levels, we used the Oculus standard hand model.

4.3.2 Methods

For the experiment, we followed a within-group design with one factor (hand) and two levels (realistic and blue hand). The IB paradigm we used requires three judgment tasks per condition: Baseline Button, Operant Button, and Operant Tone [98]. Additionally, one more condition is necessary, which is independent of hand representation realism as it does not require user input: the Baseline Tone task, where no hand was visible. Each of

Table 4.1: Study procedure. All participants finished Baseline Tone first, with no visible hand. Then they were randomly assigned a hand realism level (realistic or blue) and completed the three tasks involving a visible hand in a random order. Thereafter, they answered the embodiment questionnaire and could take a short break. Then, participants proceeded with the other hand realism level. Finally, they answered the SSQ [135], the NASA TLX [103] and the SUS [130].

Hand Realism Level	**Time Judgment Task**
-	Baseline Tone
A	Baseline Button Operant Button Operant Tone
	Embodiment Questionnaire
BREAK	
B	Baseline Button Operant Button Operant Tone
	Embodiment Questionnaire
SSQ, NASA TLX, SUS	

these seven conditions had 30 trials, resulting in 210 trials per participant. Participants spent about one hour in the VR experiment. All participants started with the Baseline Tone condition, where no virtual hand was visible. They then did two blocks of conditions with a virtual hand, one for each hand representation. The order of hand representation was counterbalanced among the participants. One block consisted of three conditions that occurred in random order for each block; see 4.1. For each hand type, the three task types occurred in random order. The experiment design can be seen in Table 4.1.

In all conditions, the participants saw a Libet clock on the virtual table. In each trial, a red dot circled the clock face, starting at a random position. The clock stopped 1 s after each trial, and the red point disappeared. In the conditions that included a button press (Baseline Button, Operant Button, Operant Tone), the users' left hand was visible during the trials either as a realistic or semi-transparent hand. After each trial, the left hand disappeared, and the users' right-hand position was visualized with a blue arrow, which was used to mark the time reporting in the Libet clock. In each condition, participants were informed via prerecorded audio files about the specific procedure of the condition via headphones. The time judgments were entered after each trial. Participants saw a blue arrow where their right hand was and could position a red marker on the Libet clock with that arrow. The time judgment was confirmed using the space bar with the left hand. Each condition is visualized in Figure 4.3.

In the Baseline Tone condition, participants watched the Libet clock and were instructed to attend to a tone (1000 Hz, 100 ms duration, like in Haggard et al. [98]) that occurred at a random time between 2.56 and 8 s. In each trial, participants marked the time when they perceived the tone on the clock face, using the blue arrow with their right hand. During

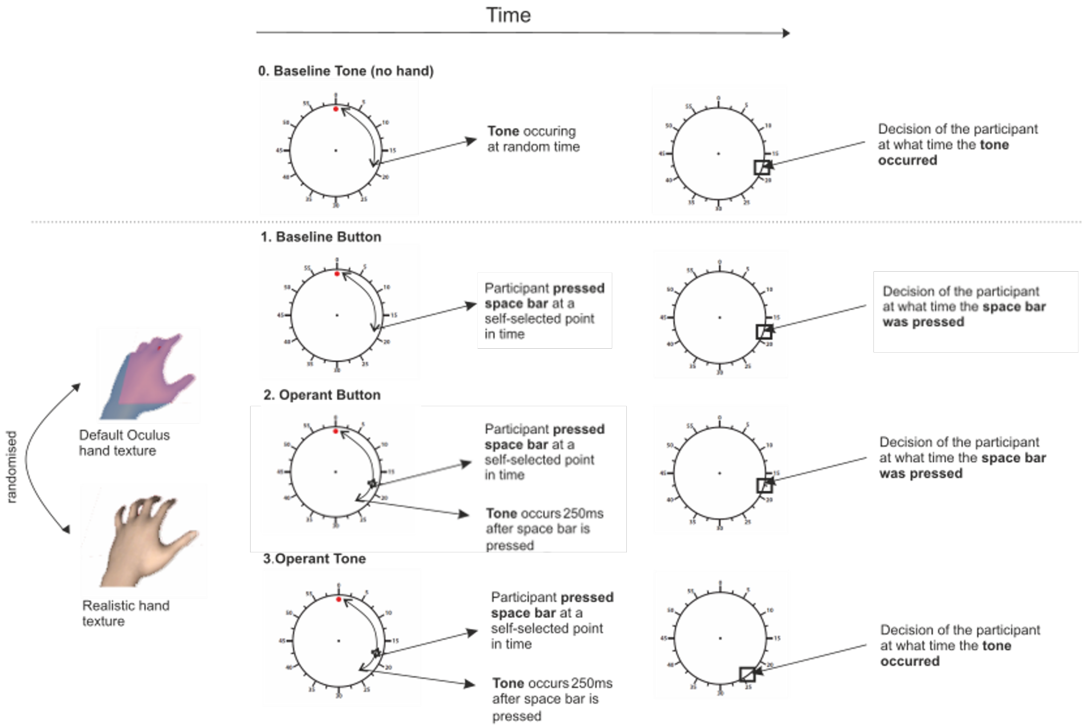


Figure 4.3: Visualization of all conditions. The clock starts at a random position and rotates with constant speed.

trials in this condition, the left hand was not visualized at all. Since it was considered the easiest to understand and would help understand the other conditions, this condition was conducted first for all participants.

In the Baseline Button condition, participants' left hand was visualized either as a realistic or semi-transparent hand. They were asked to place their left hand on the space bar of the keyboard and press the space bar at a self-selected time after the start of the Libet clock and to mark the corresponding time of the button press afterward, again with the right hand visualized as a blue arrow. No other instructions on the position of the hands were given. For the button press, participants were instructed to wait for at least one full rotation, vary the chosen time, and avoid predefined times or pressing in a repetitive pattern. However, during the execution of the study, it was noted that not all participants followed those instructions closely. Participants for whom this behavior was noticeable, e.g., because they pressed the button at the same clock position multiple times in a row, were reminded to vary timings.

In the Operant Button and Operant Tone conditions, the button press was followed by a tone with a time interval of 250 ms just as in the study of Haggard et al. [98]. Participants were asked to mark their time judgment of the button press in the Operant Button condition or the tone in the Operant Tone condition on the Libet clock after each trial. Like in the Baseline Button condition, they were asked to avoid repetitive patterns or predefined button presses and wait for at least one clock rotation. Deviating from the experiment in

Haggard et al. [98], participants were asked to repeat the respective task in all parts 30 times instead of 40 times. This reduction of trials was implemented to limit VR exposure time while maintaining an adequate amount of data with the limited number of participants.

4.3.3 Participants

We recruited 15 participants (age 19-31, m = 22.3, seven female) through personal contact who were naive to the research question. Thirteen were students or professionals in the field of human-computer interaction. Regarding handedness, thirteen were right-handed. Three of the participants used glasses for vision correction, and one used contact lenses. None of the participants reported a health condition from a given list that could interfere with the purpose of the experiment. While three participants had not used an HMD before, one reported using it every day. Most participants had only a little experience with VR. In particular, only three participants had used hand tracking before. One participant took part remotely due to COVID-19 pandemic regulations. The person was provided with the necessary equipment, and in a video call before the conduct, it was made sure that everything was set up correctly.

4.3.4 Procedure

Before the study, each participant gave informed consent and completed a demographics questionnaire and the Simulator Sickness Questionnaire (SSQ) pre-questionnaire.

Each part started with an audio instruction about the exact task to follow. Participants then had the opportunity to ask further questions. After completing all conditions for one hand type, the participants filled out the agency and ownership questionnaire.

After the second block, they additionally were asked to fill out the post-study Simulator Sickness Questionnaire (SSQ) [135], the NASA TLX questionnaire [103], and the System Usability Scale [130]. These standard measures were included to ensure comparability to previous works and to check whether the implementation of the task was well usable.

At the end, all participants were asked to provide feedback on what they noticed most during the study. They also had the opportunity to ask questions about the study and were educated about the exact purpose. Remote participants also sent in the logged results of their VR tasks to the experimenter.

The exact wording of all questions is given in Table 4.2. The first nine questions were taken from Argelaguet et al. [8], six on agency (A1-A6) and three on ownership (O1-O3). Three more questions were added on how the participants perceived the embodiment. E1 was initially used in the rubber hand experiment by Botvinick and Cohen [29] and was intended to give a more comprehensive picture of whether the realistic hand, in particular, actually gives the impression of ownership. E2 was adapted from question R12 of Peck and Gonzalez-Franco's Standardized Embodiment Questionnaire [197] and was added to obtain insights into possible tracking errors. Finally, E3 was added to gather insights into the usage of the hand-tracking technology used.

Table 4.2: Questions of the embodiment questionnaire. Participants answered on a 1-7 Likert scale, ranging from 1 = strongly disagree to 7 = strongly agree, except for Question A3. A1-O3 are taken from Argelaguet et al. [8].

ID	Question
A1	I felt as if the virtual representation of the hand moved just like I wanted it to, as if it was obeying my will.
A2	I expected the virtual representation of the hand to react in the same way as my own hand.
A3	The task was (1 = difficult, 7 = easy) to perform.
A4	I felt like I was able to interact with the environment the way I wanted to.
A5	I felt that the interaction with the environment was realistic.
A6	I felt like I controlled the virtual representation of the hand as if it was part of my own body.
O1	I felt as if the virtual representation of the hand was part of my body.
O2	I felt as if the virtual representation of the hand was someone else's.
O3	I felt that I was losing the control of my hand when the virtual hand was not responding properly.
E1	The virtual hand began to resemble my own (real) hand in terms of shape, skin tone, freckles, or some other visual feature.
E2	I felt as if my own hand was located where I saw the virtual hand.
E3	I experienced technical difficulties with hand tracking.

Table 4.3: Mean results for NASA TLX in each sub scale.

	Mean	SD
Mental Demand	3.3	1.2
Physical Demand	1.9	0.9
Temporal Demand	2.3	1.2
Overall Performance	5.1	1.0
Effort	3.2	1.3
Frustration level	2.7	1.8

4.4 Results

The System Usability Scale resulted in a score of 79.5, which can be interpreted as good usability [20]. The NASA TLX results can be seen in Table 4.3.

The results show that while the task was mentally demanding to some degree and required effort, the participants were mostly satisfied with their performance. Mean SSQ values increased from 1.17 pre-VR exposure to 1.31 post-VR. This shows little evidence of problems affecting the study's validity in that participants felt sick after VR exposure.

Table 4.4: Results of the Intentional Binding Paradigm. Mean errors in ms.

	Button		Tone	
Baseline	Blue	Realistic	146.0	
	-17.3	-18.3		
Operant	Blue	Realistic	Blue	Realistic
	-20.4	-20.2	49.6	45.9

4.4.1 Intentional Binding

To analyze the data for the IB task, we first calculated the judgment errors in each trial. In the Button conditions, the difference between the real timing of the button press and the reported timing of the button press was calculated; in the tone condition, the error between the tone and the reported timing of the tone was calculated. The mean errors in milliseconds can be seen in Table 4.4. A negative value indicates that participants estimated the time of the event earlier than it actually happened. We ran an outlier detection algorithm and found 14 data points that we removed from the data set before aggregation. One participant was excluded from this analysis because of the wrong execution of the task.

The timing judgments in the Baseline Button conditions were fairly accurate, with a mean error of -17.3 ± 31.8 ms using the blue hand and -18.3 ± 34.1 ms using the realistic hand. In the Operant Button conditions where the button press was followed by an auditory stimulus, participants had a mean error of -20.4 ± 32.1 ms or -20.2 ± 41.0 ms with the blue hand or the realistic hand, respectively.

To compare the results of these conditions, a three-way repeated measures ANOVA was conducted. Normality was checked using the Shapiro-Wilk test. The analysis showed no significant effect of either the condition, meaning baseline or operant ($F(1, 13) = 0.700,\ p = 0.418,\ \eta_g^2 = 0.002$), the hand representation ($F(1, 13) = 0.030,\ p = 0.865,\ \eta_g^2 = 0.000161$), the order of the conditions ($F(1, 13) = 0.349,\ p = 0.565,\ \eta_g^2 = 0.022$), or any combination of them (e.g., condition and hand representation $F(1, 13) = 0.008,\ p = 0.931,\ \eta_g^2 = 0.0000338$).

The mean error in the Baseline Tone condition was 146.0 ± 52.3 ms and in the two Operant Tone conditions 49.6 ± 59.9 ms and 45.9 ± 34.7 ms with the blue and the realistic hand, respectively. A two-way repeated measures ANOVA revealed a significant difference between these three conditions ($F(2, 24) = 16.927,\ p = 0.000026,\ \eta_g^2 = 0.469$) but no effect of order ($F(1, 12) = 0.003,\ p = 0.958,\ \eta_g^2 = 0.0000884$) or the combination of condition and order ($F(2, 24) = 0.156,\ p = 0.856,\ \eta_g^2 = 0.008$). Post-hoc t-tests with a Bonferroni adjustment showed a significant difference between the Baseline Tone condition and the Operant Tone condition for the blue hand ($t(13) = 4.31,\ p = 0.003$) and the realistic hand ($t(13) = 5.13,\ p = 0.000576$) but no difference between the different hands in the Operant Tone conditions ($t(13) = 0.314,\ p = 1$), see Figure 4.4. An additional ANCOVA analysis with results of the agency and ownership questionnaire as a covariate did not reveal a relationship either (e.g., $F(1, 2) = 1.279,\ p = 0.376,\ \eta_g^2 = 0.194$ for question A1).

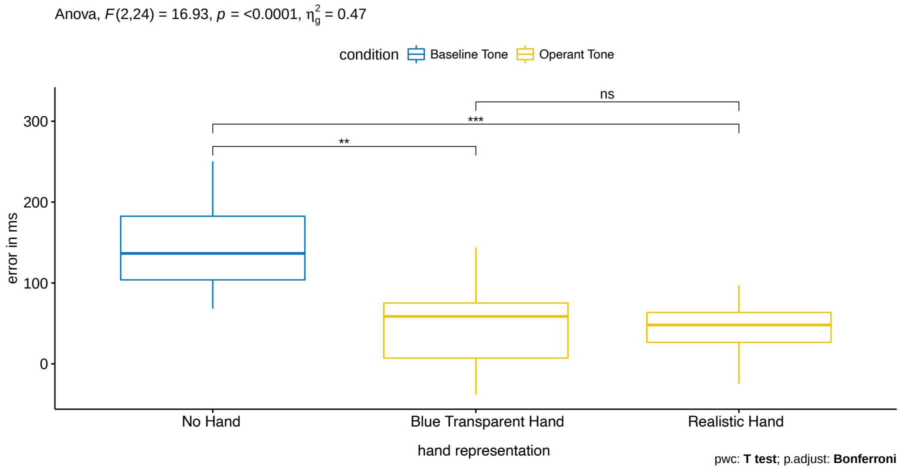


Figure 4.4: Judgment error in Baseline Tone condition and both Operant Tone conditions. Box plots show the median and first and third quartiles. The whiskers show a 1.5 × interquartile range. ***: p < 0.001, ** p < 0.01.

To get a more profound insight into the effect of hand representation, we additionally used Bayesian statistics to analyze the data. As suggested by Biel and Friedrich [22] in a neurological context, reporting Bayes Factors for non-significant results allows seeing a trend in the data. As it is based on the Bayesian view of probability, it is possible to see if there are effects in the data, which might not be significant in standard null hypothesis significance testing (NHST). Using a Bayesian two-sample paired t-test, we found a Bayes factor of 0.281 for realistic or default hand representation. According to Andraszewicz et al. [6] this means moderate evidence for H_0, stating both samples are equal.

4.4.2 Subjective Agency

4.4.2.1 Questionnaire

The results of the embodiment questionnaire (see Figure 4.5) for both hand representations were compared also using the paired samples Wilcoxon test. It showed a significant effect only for E1 ($r = 0.820$, $p = 0.0035$). The realistic hand reached a mean score of 3.7, whereas the default blue hand scored 2.1. However, the results hint at the fact that the realistic hand might have scored slightly worse than the default hand in terms of ownership and agency, as can be seen in questions A1, A5, and O1. Control question O2 showed a slightly higher score for the realistic hand. However, these differences are not significant.

4.4.2.2 Preferences and free comments

During the experiment, participants were free to comment on their impressions. After finishing the last questionnaire, they were asked if they wanted to mention anything about their experience. In this section, we aim to summarize this feedback.

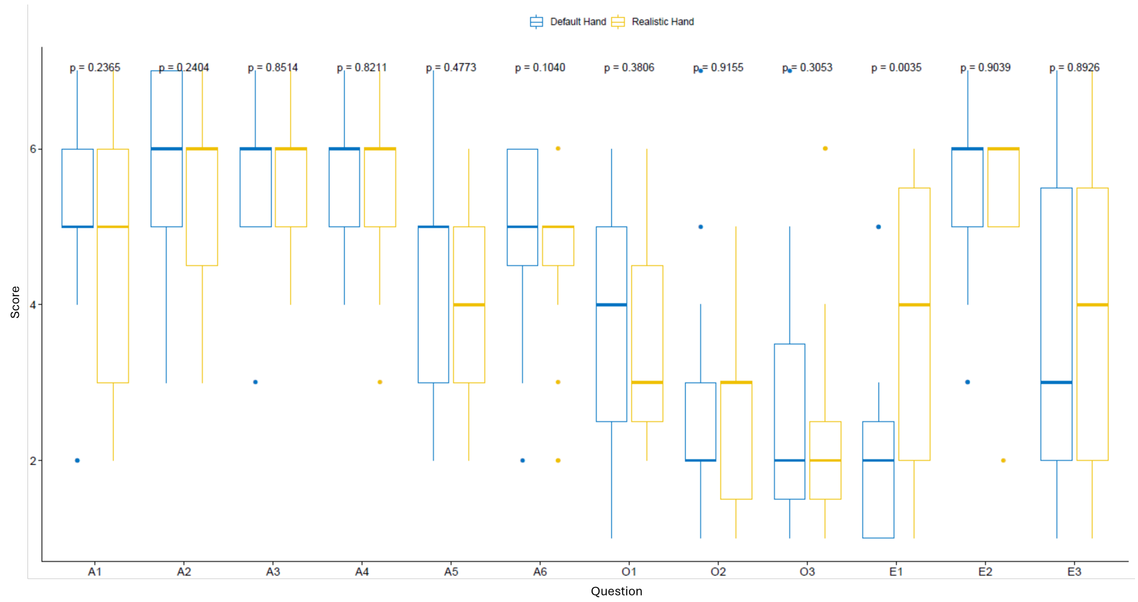


Figure 4.5: Results of the embodiment questionnaire for both hand appearances. Box plots show the median and first and third quartiles. The whiskers show a 1.5 × interquartile range.

Comparing the two hand representations, five participants reported a subjective preference for the blue hand over the realistic one, i.e., they felt less control over the realistic hand and were more distracted as it did not match their actual hand in terms of detailed visual features. Two participants explicitly mentioned irritation about the skin color in VR or their virtual fingers not matching the length or thickness of their actual fingers.

Furthermore, five participants reported disturbance by seeing their virtual fingers shivering, their hands floating around, or flickering in some situations, e.g., when they were brought together, causing the impression of their virtual hand being a tool rather than creating an embodiment illusion. Interestingly, three participants felt more disturbed by this when they used the realistic hand representation. Two participants thought the default blue hand to be more practical as it was transparent.

4.5 Discussion

The results suggest that an SoA was achieved with both hand representations equally. This could be found with an implicit as well as an explicit measure. In the following, these findings are discussed in the context of related works.

4.5.1 IB Effect

In our study, tone judgment shifted from +146 ms in the Baseline Tone condition to 49.6 ms in the Operant Tone Blue condition and 45.9 ms in the Operant Tone Realistic condition, resulting in a difference of -96.4 and -100.1 ms, respectively. These values are in a very similar range as reported in the second experiment of Haggard et al. [98]. They found auditory tone judgment shifting from -6 ms in the baseline condition to -103 ms in the Operant Tone condition with an interval of 250 ms, resulting in a shift of -97 ms. This very likely implies that this shift can be traced back to the so-called IB effect, as other explanations for a perceptual shift are unlikely to elicit such a strong effect [98].

In the Button conditions, we found shifts between Baseline and Operant of +3.1 for the blue hand and +1.9 for the realistic hand. Haggard et al. also reported a smaller effect size for Button size, with 15 ms in [98]. However, the precision of the judgments given by subjects in this study matches that in the previous literature ([98]: 6 ms judgment error in the baseline, 21 ms in the operant condition, compared to 17.3 to 20.4 ms in the study conducted here). Overall, the values show very high similarity with previous comparable experiments and can therefore be interpreted as the result of the IB effect.

However, no effect of hand appearance on IB could be found.

4.5.2 Subjective Agency

The results of the embodiment questionnaire showed no significant effect of hand representation for any of the sub-scales: Agency, Ownership, or Embodiment. Argelaguet et al. [8] reported decreased SoA with increasing hand realism level and increased SoO for increased hand realism level. The differences in findings could be related to the different hand realism levels in both works. While in Argelaguet et al. [8] the hands had different degrees of freedom and different visual abstraction levels; in our works, degrees of freedom were identical, and only the visual appearance differed. It suggests that agency and ownership rather depend on degrees of freedom than the visual abstraction level. This is also in line with findings from Ogawa et al. [193]. They used three different hand realism levels, two of them fully articulated hands, and could find significant effects only between both fully articulated hand models and the non-articulated block hand model, not between both fully articulated hand models.

Still, in our work, participants felt more distracted by the shivering movements of the more realistic virtual hand, which suggests different expectations towards the virtual hands depending on appearance realism.

4.5.3 Effect of Hand Representations on Agency

In this work, we could not find a significant effect of hand representation on SoA. Although some works reported an effect [8, 193], others did not find it [133, 146, 157, 287], suggesting a small effect size. As due to the current regulations it was challenging to recruit participants, our sample size might have been too small to detect this effect. Also, our analysis using Bayesian statistics did not reveal any trend in IB.

It is possible that the visual difference in the hand representations used was too small to be detected by this experiment. Whereas other studies comparing hand perception for different hand models used abstract or iconic depictions, limiting the degrees of freedom [8, 193], in our work only different textures were evaluated. Still, some participants felt more distracted by the shivering movements of their more realistic virtual hand, which suggests a change in the perception of the virtual hands depending on their texture. Moreover, although not statistically significant, we observed lower agency ratings using the questionnaire. This interpretation supports the findings of Argelaguet et al. describing a declining SoA for more realistic hands connected to the higher expectations of a realistic-looking hand [8]. So, for future work, it would be interesting to replicate their setup and see if the effect can also be found using the IB paradigm.

Overall, participants did not spend as much of their time in VR interacting with their hands as they would typically do in VR games or applications. Some participants explicitly stated they did not pay any attention to the look of their hands during the task. This lack of experience with their virtual hand may have affected the SoE they felt for it [145]. Moreover, the relatively long duration of the experiment of 60 to 90 minutes may have led participants to at least pay less conscious attention to aspects not directly related to the task. A between-subjects study design may avoid this and allow subjects more time to develop a feeling of embodiment. However, participants would also experience one hand realism level and could not comment on personal preferences for each hand model.

As mentioned previously, the SoE apparent in questionnaires also appears to be sensitive to the temporal proximity of the conduction of the questionnaire to the experience inducing the SoE which might be an additional error source [145].

The fact that the binding effect without any training was stronger than in the study by Kong et al. may result from the difference that they used prerecorded footage of somebody pressing a button, which was shown to the subjects in VR from a first-person perspective [145]. Those perceptions only elicit a vicarious agency that does not require intentional action but still creates a feeling of agency [268].

The realistic hand not leading to a measurably stronger IB could also be related to the uncanny valley effect, as it has been described by Mori [185]. It results in a significant drop in affinity for a human-like depiction when it reaches a high similarity to real human limbs but does not match them perfectly. Mori explains this with the visual similarity to dead bodies. Although no subject showed a clear aversion against the realistic hand representation, the affinity for it may have been affected, resulting in similar degrees of affinity for both hands. This is consistent with some participants' statements that the hand depicted did not look similar enough to their own and with the widespread responses to question E1 after the realistic hand block. This negative impact on embodiment may have been amplified for both hands by the missing representation of an arm, as watching body discontinuity was shown to reduce perceived ownership and vicarious agency [252]. Despite the differences in our setup, i.e., not showing an arm at all and targeting the SoA instead of the vicarious agency, it may have prevented a stronger ownership or agency experience. Because of the technology used, displaying the arm was not easily possible but should be kept in mind for further research in this field.

More than any other factor, the lack of precision in the tracking probably affected the feeling of embodiment. The spontaneous trembling of the hands or the sudden hovering of the virtual hands in space led to a massive distraction for many subjects. Five participants stated that the hands felt more like a tool that could be controlled by their hands, but not like their own hands because of this. That is supported by Kilteni et al., stating that incongruities and especially timing differences between the real body and its virtual depiction disturb the SoA [136].

Another possible objection would be the input method and precision not being sufficient or appropriate, as it is also affected by the imperfect tracking technology. In addition, there is a possible bias due to the horizontal clock face, causing some positions to be easier to reach. While it is possible that an insufficient input precision shallowed minimal effects, the other objections are contrasted by the evident binding effect shown in the tone condition and the results of the control questionnaires. Neither did NASA TLX show a task overload, nor did the SUS hint at bad usability. Also, the input precision did not vary depending on the clock position at the considered event. A Pearson correlation found no significant linear relationship ($R = 0.01,\ p = 0.57$).

Regarding our research questions, We could not find an effect of hand appearance on SoA (**RQ1.1.1**). For **RQ1.1.2**, we neither found a significant effect on the objective IB paradigm nor on the subjective questionnaire. However, while Bayesian statistics suggest there is no trend in the IB data, the median result for the embodiment subscale was higher for the realistic hand than for the blue hand, but not significantly. In summary, no effect of hand representation on SoA could be found in our setup using both implicit and explicit measures.

4.6 Limitations

First, several technical limitations resulted from the VR technology used. The Oculus Quest 2 uses multiple cameras placed on the outside of the HMD. The Oculus camera tracking technology has several precision issues resulting from that limited perspective. As mentioned by Oculus itself, occlusion by either objects or parts of the hand by the hands themselves or leaving the tracking volume can lead to unsatisfying tracking results [4]. Although participants were encouraged to avoid those situations by keeping their hands in a suitable position and pose, this was one of the main issues reported by participants during and after the study. As a result, their virtual fingers appeared to shiver, especially when they placed their hands in an ergonomic position (see Figure 4.6), which occluded some parts of their hand. But also, if the hands were placed in a way that is recommended by Oculus [5], many participants experienced the whole virtual hand to shiver in contrast to their actual hand being entirely still. As the setup required them to keep their left hand

[4] https://developer.oculus.com/resources/hands-design-intro/

[5] https://developer.oculus.com/resources/hands-design-bp/

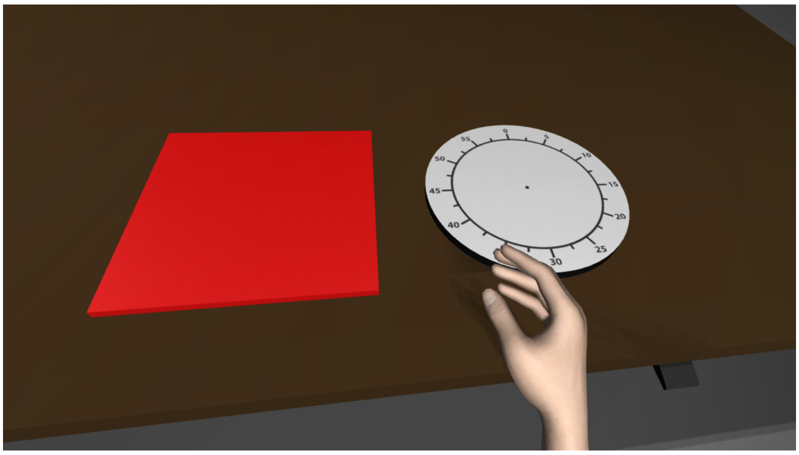


Figure 4.6: Ergonomic hand pose with high self-occlusion. The partial occlusion of fingers can cause imprecise tracking results or unexpected movements of the virtual fingers.

in almost the same pose during the entire VR experiment, this effect was more notable than in a setting with constant interaction by moving their hands.

Moreover, only one realistic hand representation (see Figure 4.6) was used for all participants. That caused the degree of similarity to vary between the subjects and is expected to influence the SoO. Argelaguet et al. met this problem by limiting the group of people who could take part to males, as they matched the virtual hand presented to them more closely [8].

Since this setup relied on the hand tracking provided by Oculus only, the participants only saw a virtual representation of their hand without an arm or the rest of the body. Other studies showing a virtual arm to the subjects used prerecorded footage or different tracking technology that would have made the remote study setting much more difficult [8, 145, 252]. However, this may have negatively influenced the embodiment, as shown in body discontinuation VR experiments by Tieri et al. [252]. To encourage participants to not look directly onto the wrist surface, the clock face was placed on the table instead of behind the desk. However, this could have created some minor distortion effects.

Apart from that, due to a misconfiguration of the Oculus SDK, the virtual hands of the first five participants were not adjusted to their actual hand size. Three of them reported that they felt irritated by that mismatch. The measurements of one of those subjects were excluded from the analysis.

Because of the restrictions during the COVID-19 pandemic, the study could not be conducted in the laboratory of our working group. Instead, students and academic staff who had an Oculus Quest 2 available took part remotely. This limited the number of participants and may also have biased the subject selection, leading to a group of participants with high technical expertise.

4.7 Conclusion

This work investigates the effect of differences in the depiction of virtual hands in immersive scenarios on SoA as a part of embodiment by using the IB paradigm. The analysis showed a perceptual shift in the temporal perception of the auditory stimulus for both hand representations, and the effect size was comparable to that in the literature [98, 145]. This confirms the suitability of our setup, similar to Haggard et al. [98], to measure an IB effect in VR.

However, the two different hand representations showed no effect on SoA. Regarding the questionnaires, there was also no significant difference in most questions between both hands. Analysis for other variables, i.e., the order of the hand representation blocks possibly affecting the results, did not show an evident effect either. Despite a hint of a small tendency towards the realistic hand eliciting a slightly weaker embodiment experience, which would be congruent with statements of some participants after the study and previous findings suggesting higher expectations of the realistic hand being a reason for that [8], we found no evidence for differences between the two hands.

You et al. [280] suggested that agency questionnaires should be refined to better capture SoA. Using the same questionnaire as Argelaguet et al. [8], we did not find a significant difference for hand realism level, while in their work there was a significant effect. In contrast to Argelaguet et al. [8] we used only two different hand models, both anthropomorphic. We assume that the different hand models and other differences in the setup led to the different results.

Regarding **RQ1.1**, we can conclude that our data does not indicate any effect of hand appearance in terms of realism and truthfulness on SoA, given the same morphological structure (anthropomorphism). We assume that the effects of hand appearance on agency reported in other studies [8, 193] might be related to different layouts of the virtual hand, leading to limited functionality and diverging mapping between the real and the virtual hand.

4.8 Future Work

We identified some possible improvements for future works. First, there were several factors, such as the unsatisfactory tracking results of the Oculus hardware and software, the missing arm representation, and a lack of training time allowing the subjects to build a SoA over time and identify with their VR hand [145]. Moreover, the hands differed only in texture, which may have been too subtle to produce a visible difference in the SoE, since a previous study implemented a greater variety of hand models [8].

To address these experiment issues, further investigation is needed to clarify the reasons for the missing difference. Future research could try to increase the SoO by using a custom hand model that has a higher similarity to the subject's hand [136], increasing the difference between the hand representations. An outlook on a pipeline to create such photorealistic hands will be presented in Chapter 7.

In the next chapter, Chapter 5, we will investigate another factor that contributed to the illusion of virtual hands: redirection sensitivity for hand redirection. Redirecting virtual hands can be done noticeably to enhance the users' interaction space or to increase ergonomics. However, in such cases the self-attribution of the virtual hands and the (SoA) can be decreased [136, 225, 268]. Wether unnoticeble redirections however, influence SoE, hasstarted to be investigated [65, 192, 284]. We further investigate the underlying factors of redirection sensitivity for a gain-based redirection method, including handedness, as well as movement axis and movement direction.

5

Detection Thresholds for Hand Redirection

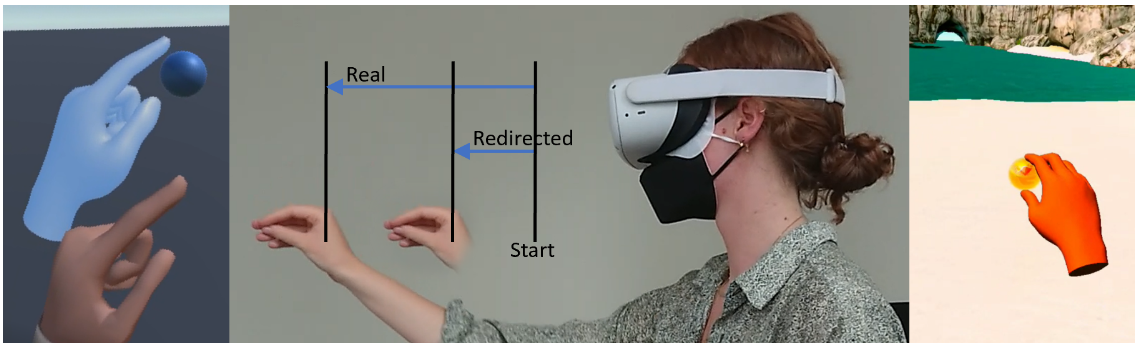


Figure 5.1: Left: In a psychophysical experiment, we evaluated detection thresholds for a gain-based hand redirection method in VR for different motion directions. The blue hand visualizes the participant's real hand. Center: In the decelerated mode, the real hand had to be moved further to reach a virtual object. Right: We applied the determined detection thresholds in a playful application and could confirm our findings.

In this chapter, we present a psychophysical experiment, analyzing detection thresholds for six different motion paths in midair for both hands. We use a whole-body avatar with fully articulated hands and personalize the arm length and hand size for each participant to ensure a high level of embodiment and to improve user experience [139]. To verify our findings, we applied the identified gains in a playful application in a confirmatory study. This chapter investigates **RQ1.2** and is based on the following publication:

J. Hartfill, J. Gabel, L. Kruse, S. Schmidt, K. Riebandt, S. Kühn, and F. Steinicke. "Analysis of Detection Thresholds for Hand Redirection during Mid-Air Interactions in Virtual Reality". In: VRST '21: Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology. Osaka, Japan: Association for Computing Machinery, 2021. ISBN: 9781450390927. DOI: 10.1145/3489849.3489866

5.1 Introduction

We present a psychophysical experiment based on a staircase design with 20 participants to determine how much discrepancy between virtual and real hands remains unnoticed by the users. With this technique, users need to perform larger movements to reach for an object in the VE, which can be utilized, for example, in therapeutic applications. For this purpose, we applied a gain-based hand redirection method along all three spatial axes, with a focus on decelerated virtual hand motions. In the analysis, we particularly considered differences between detection thresholds for the dominant and non-dominant hand, as well as for both motion directions per axis. Finally, for a confirmatory study with six participants, we developed a playful application in a therapeutic context in which we applied the derived detection thresholds.
To summarize, the contributions of this chapter are the following:

- Analysis of detection thresholds for hand retargeting during midair interactions along all three spatial axes, including two motion directions per axis and both hands.
- Evaluation of the detection thresholds in a confirmatory study with a playful application that encourages arm movements.

The remainder of this Chapter is structured as follows. Section 5.2 outlines previous work related to rehabilitation using VR. In Section 5.3, a gain-based hand redirection method is introduced. Section 5.4 describes the psychophysical experiment we conducted to determine how much hand redirection can be applied without being reliably detected by users. The section is concluded by a discussion of the results and limitations of the chosen experimental design. In Section 5.5, we briefly present a confirmatory study where we applied the detection thresholds derived in the experiment in a playful application. Section 5.6 briefly summarizes the limitations of this work, and Section 5.7 concludes this work and gives an overview of future work.

5.2 Related Work on VR Rehabilittion

The general potential of VR for various therapeutic applications has already been demonstrated by several research projects. VR can provide intensive, repeatable, and task-oriented training, thus increasing patient enjoyment during therapy [42]. For example, mobile game-based VR rehabilitation was shown to be effective for upper limb recovery after ischemic stroke and even yielded greater improvements than conventional therapy [42]. Furthermore, VR has been suggested as an effective supplement to medications for pain control. It has been shown that diversion from the real environment by immersion in a VE can attenuate a patient's pain perception and discomfort [170]. For Parkinson's disease (PD), VR was also shown to be an effective rehabilitation tool with potential added value over traditional physical therapy approaches. For example, Dockx et al. showed that VR can optimize motor learning in a safe environment and improve functional activities of daily living by recreating real-world scenarios [54]. Feng et al. conducted a VR rehabilitation study, showing greater improvements in balance and gait of individuals with PD compared to conventional physiotherapy [69]. In the same context, Janeh et al. [125] could successfully demonstrate that redirection of the feet can be used to improve gait symmetry in patients with PD. Similarly, such applications might have great potential for upper limb rehabilitation, for example, for the treatment of phantom limb pain and therapy for stroke patients [57, 219, 267].

5.3 Hand Redirection Method

In this section, we describe the implementation of the hand redirection method that we used in this work.

For tracking the hand movements and displaying the VR content, we used the Oculus Quest 2, which is a standalone HMD with built-in, fully articulated hand tracking. We generated a rigged full-body 3D avatar using the platform Ready Player Me[1]. For controlling the avatar with tracking data from the Quest 2, we used the Hand and Arm Movement Manipulation Framework [81], which was developed and provided for the Unity engine, version 2019.4 LTS. The framework is based on the Oculus Integration[2] and the Animation Rigging Unity package[3]. It maps the tracked head, hand, and finger poses onto the respective bones of an avatar's armature, sets up inverse kinematics (IK) arm controls, and can apply different movement manipulations. The avatar's IK arm movements use the *Two Bone IK Constraint* from the Animation Rigging package. The IK control is based on the tracked hand root (wrist) positions and additional hint positions for controlling the placement of the elbows.

For implementing the redirection technique, we use a linear, translational *gain* on all three spatial axes (x, y, z) in the VE, similar to the gain-based methods in [65, 284]. The redirection is applied to the 3D position vector of the avatar's hand root bone. The redirected position of the virtual hand $\vec{p}_r$ is calculated by multiplying the last movement of the real hand $\vec{p}_t - \vec{p}_{t-1}$ with the gain factor g and adding that vector to the current virtual hand position $\vec{p}_{v-1}$, see Algorithm 1.

Hence, gain factors $g > 1$ lead to an accelerated movement and $0 < g < 1$ lead to a redirection with decelerated movements, as can be seen in Figure 5.2.

[1] https://readyplayer.me/de
[2] https://developers.meta.com/horizon/downloads/package/unity-integration/
[3] https://docs.unity3d.com/Packages/com.unity.animation.rigging@0.2/manual/index.html

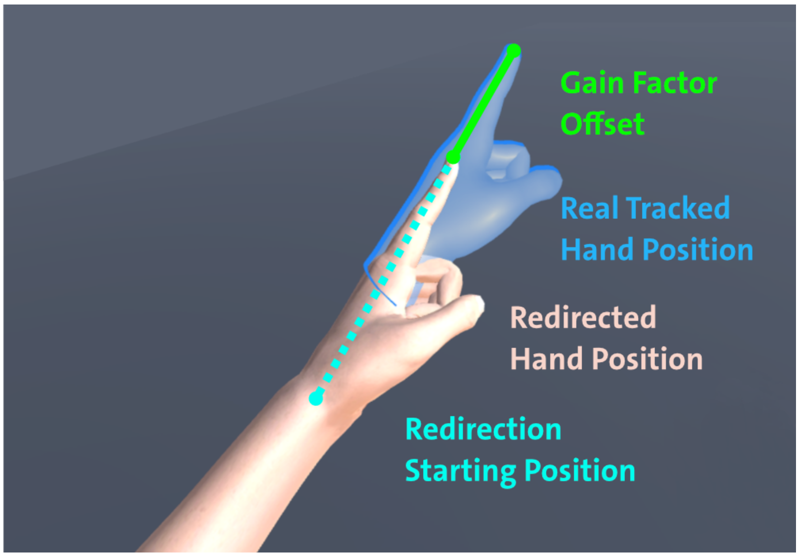


Figure 5.2: Gain factor offset between the real and virtual hand for the decelerated hand movements.

Algorithm 1: Gain Calculation

Input: current tracked hand position $\vec{p}_t$, last tracked hand position $\vec{p}_{t-1}$, last virtual hand position $\vec{p}_{v-1}$, gain factor g

Output: current virtual hand position $\vec{p}_v$

$\vec{a}_r = (\vec{p}_t - \vec{p}_{t-1}) * g$ ▷ *redirection amount*

$\vec{p}_v = \vec{p}_{v-1} + \vec{a}_r$ ▷ *final redirected position*

return $\vec{p}_v$

5.4 Experiment

We conducted an experiment to investigate decelerated hand movements in VR, considering both movement directions on all three spatial axes using a staircase procedure. Participants performed six different motions with each hand, with different gains applied. After each trial, they were asked to decide if the virtual hand movement was identical to their actual hand movement. From that, we derived a detection threshold for each movement direction.

5.4.1 Overview

Previous work in this field estimated detection thresholds based on data of one hand only. Whether these thresholds can be directly applied to the other hand remains unclear. We hypothesized that detection thresholds differ between hands. Due to training effects, proprioception might be more reliable for a user's dominant hand. This could reduce the visual dominance effect and, consequently, result in a higher sensitivity to detect redirections. Esmaeili et al. [65] have already shown that detection thresholds differ depending on the spatial axis, and Ogawa et al. [193] found an increased sensibility for

outward redirections. Therefore, we hypothesized that detection thresholds depend on movement direction per axis. In particular, for gain-based retargeting, we expected to observe effects that are similar to angular-based redirection methods.
In summary, our hypotheses are:

H1: Redirection thresholds on each spatial axis differ between movement directions on that axis.

H2: Redirections of the dominant hand are more easily detected than redirections of the non-dominant hand.

5.4.2 Staircase Procedure

To evaluate detection thresholds as precisely as possible, we chose a double staircase design. For each condition, we formed two interleaved staircases. All descending staircases started at gains 1.0 for *decelerated* movements and 1.6 for *accelerated* movements, while all ascending staircases started from gains .4 and 1.0, respectively. In each step, the applied gain was based on the participant's last answer in the same staircase. If participants did report that the virtual movement was identical to their movement, the gain was increased by .1 for *accelerated* and decreased by .1 for *decelerated* conditions in the next trial of the staircase. Conversely, if the participant reported that the motions were not identical, the gain was decreased by .1 for *accelerated* conditions and increased by .1 for *decelerated* conditions; see Figure 5.3.

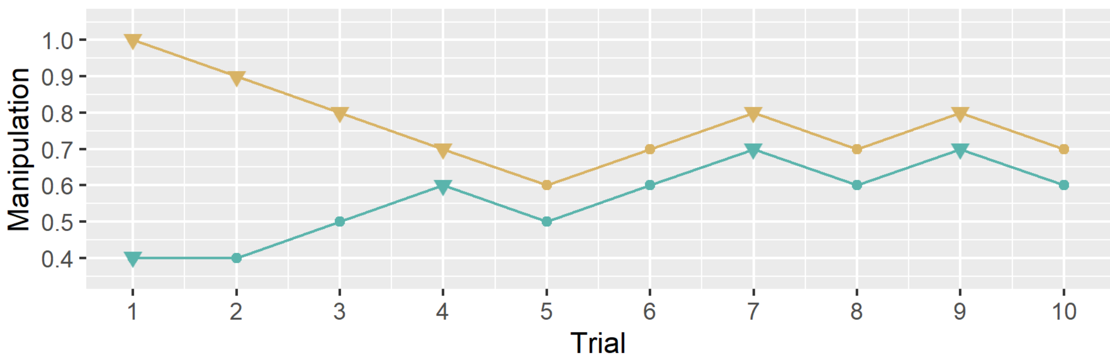


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Figure 5.3: Example data of manipulation amounts from both staircases in one condition. Triangles indicate trials judged as *identical*, and dots as *not identical*.

New gain factors never exceeded the extreme values for each mode. For example, if a participant stated .4 to be identical to their own motion, the value was not lowered, but the same value was used again in the next step.

The experiment followed a within-subjects design with three factors: *Hand* with two levels (*dominant* and *non-dominant*), *Movement Direction* with six levels (*inward*, *outward*, *upward*, *downward*, *forward*, and *backward*) and *Redirection Method* with two levels (*decelerated*

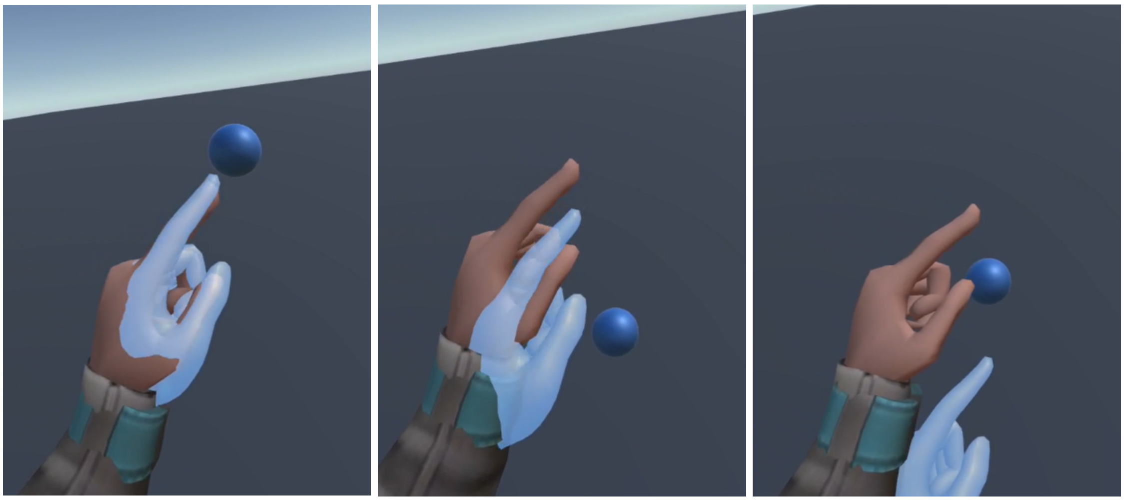


Figure 5.4: Approaching start and target sphere of one trial. The blue hand visualizes the participant's actual hand and was not visible during the experiment. The offset between the real and virtual hand increases when approaching the target sphere.

and *accelerated*). Each participant performed 480 trials by proceeding through 48 staircases in parallel (*Hand* (2) x *Movement Direction* (6) x *Redirection Mode* (2) x *Staircase Starting Point* (2)) with 10 steps each.

To avoid a possible noticeable connection between the answer to one stimulus and the next step of the staircase, all staircases developed in parallel. Therefore, participants started the experiment by proceeding through all first trials of all staircases in random order, followed by the second step of each staircase in another random order. Left- and right-hand trials were alternated to avoid stronger fatigue symptoms on one hand.

We chose .4 as the minimum value for our setup, which includes the smallest reported detection threshold by Esmaeili et al. [65] for a no-distraction scenario (.67). Although we were especially interested in decelerated motions, we also tested gain values > 1. By including them in the setup, we prevented participants from adapting to the investigated redirection method. We decided to include values up to 1.6, which includes the highest reported value for accelerated hand movement by Esmaeili et al. [65] (1.53).

5.4.3 Setup and Environment

For each trial, participants had to perform a motion between two spheres with one hand (*trial hand*) and state if the virtual motion was identical to their actual motion on a user interface (UI) using the other hand (*UI hand*). Both the UI and the spheres were color-coded (blue for the left and white for the right hand) and only reacted to the correct hand. Only one sphere was visible at a time. When touched, it disappeared, and the associated target sphere appeared (see Figure 5.4).

After touching the start sphere, the currently evaluated gain was applied. When the target sphere was touched, it disappeared, the UI appeared, and the gain on the trial hand was set to 1. Note that although the manipulation was stopped, the potential offset

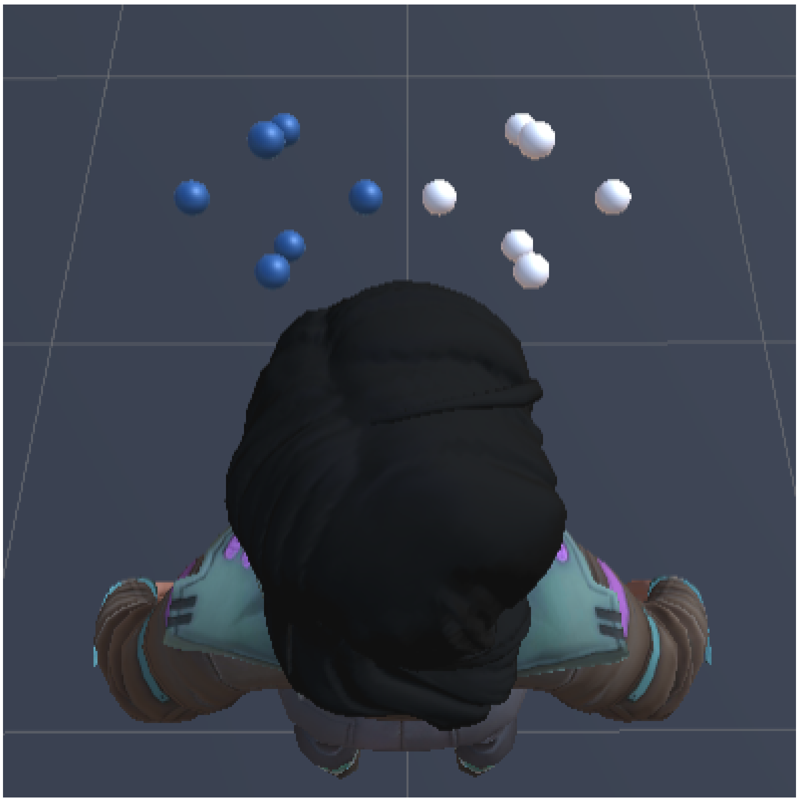


Figure 5.5: Experiment setup with all possible starting and target positions from a third-person view. Only one sphere at a time was visible.

between the virtual hand and the real hand remained to avoid a visual "snapping" of the virtual hand, which could have revealed the manipulation. The potential offset of the trial hand was reset the moment the *UI hand* touched the UI, and therefore, the participant's attention was drawn away from the *trial hand*. No participant reported noticing the reset.

Each hand had six possible target positions, two on each spatial axis. To each target position, a starting position on the same spatial axis was assigned. In total, six different movements were evaluated for each hand: both directions on all three spatial axes. The spheres had a diameter of 2 cm and appeared at a distance of 20 cm from each other. The spheres for each hand were centered around a 3D point about 20 cm in front of the avatar's respective shoulder. The setup is visualized in Figure 5.5.

For the user study, we used the Oculus Quest 2 in a tethered Oculus Link setup, connected to a laptop with an Intel Core i7-10875H processor and Nvidia GeForce RTX 2080 Super Max-Q GPU.

5.4.4 Participants

A power analysis indicated that a sample size of $N = 20$ would allow for detecting medium main effects (Cohen's $f = .3$) with 81% power using an ANOVA with an alpha level of .05 [62]. Since we had to exclude the data of the first three participants due to a bug in the VR environment, we recruited 3 additional participants. Thus, a total of 23 subjects participated, of which 20 subjects were included in the analysis (8 female, 12 male), aged from 20 to 40 (M = 25.3, SD = 4.53). All participants were recruited through student mailing lists at the local university. The majority of them were students or employees in the field of human-machine interaction. 12 participants reported having no visual impairment, and 8 participants wore glasses or contact lenses during the experiment. The majority (17 participants) stated that they had used an HMD before. 8 participants had experience with hand tracking. According to an inventory of handedness [259], we found a strong hand dominance for all participants, and it could be determined that 18 of them were right-handed while 2 were left-handed. All participants signed an informed consent form. The experiment was approved by the ethics committee of the hospital involved in this work.

5.4.5 Procedure

Participants were first asked to fill in a demographics' questionnaire, as well as the Edinburgh Handedness Inventory - Short Form, as proposed by Veale [259], and the Simulator Sickness Questionnaire (SSQ) [215]. Then they were asked to put on the HMD and were given time to familiarize themselves with the VE and hand tracking. The avatar's arm length was adapted for each participant, as well as the hand size, such that the fingertips of the index finger were well aligned.

As we wanted to derive a conservative estimation of detection thresholds, we visualized the offset between the real and virtual hand before the experiment so that participants were familiarized with the applied manipulation. For this initial introduction, both the manipulated avatar hand and the real hand were visualized in the VE. Furthermore, the highest and lowest gain values for the decelerated (.4 and .9) and accelerated (1.6 and 1.1) modes were presented and explained on one hand, while the other one was not redirected to allow participants a direct comparison. Participants were informed that the blue hand representing the real hand position would not be visible in the actual experiment and that the virtual hand could or could not be redirected during the task. When the participants agreed that they understood the manipulation modes, the task was explained, and they could do some test trials. Participants were informed that they could take a break whenever they needed. After half the trials, the participants were also offered to take a break. Participants spent about 30 minutes in the VE. When they had finished the task, participants were asked to fill in the SSQ for a second time to allow for a pre-post comparison. Finally, participants answered the Avatar Embodiment Questionnaire [197].

5.4.6 Results

For each participant, we determined detection thresholds for each of the 12 conditions (*Movement Direction* and *Hand*) from both ascending and descending staircases. We analyzed the reversal points of all staircases and found that in 97.86% of the cases a reversal appeared at the latest in the sixth trial of the staircase. Therefore, we decided

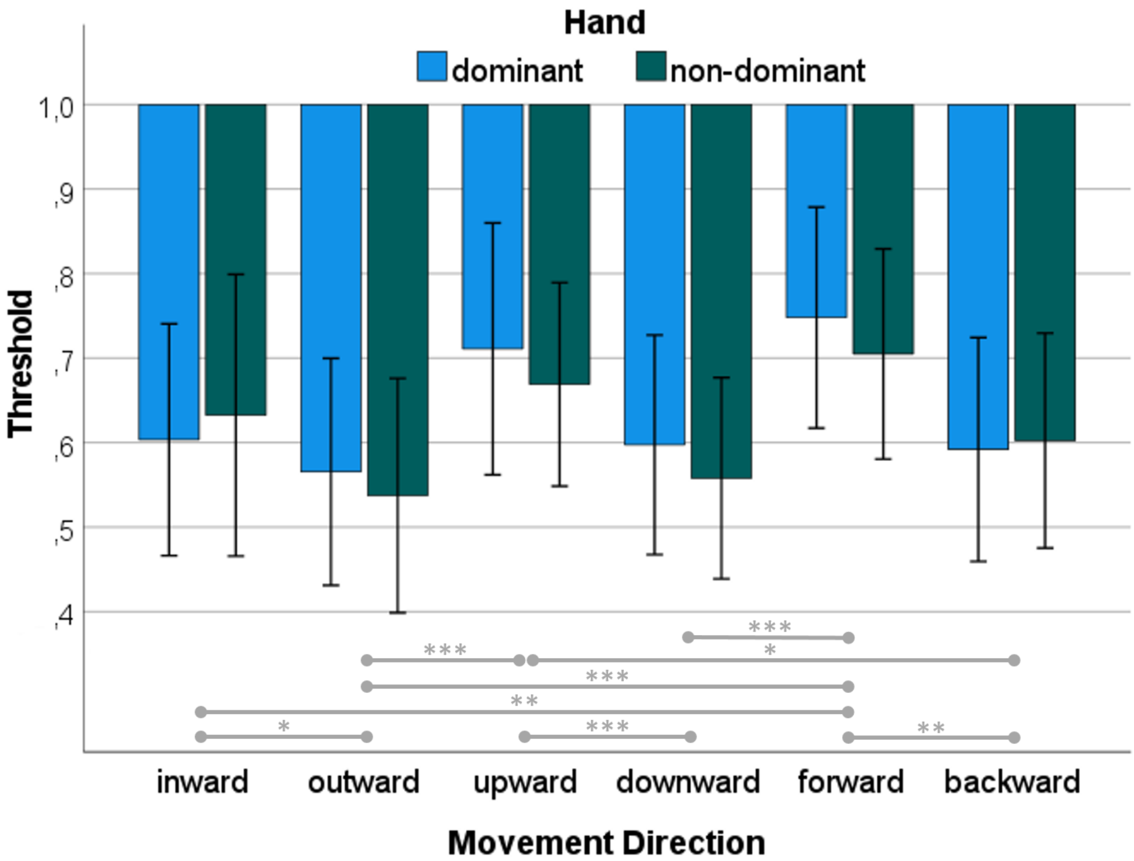


Figure 5.6: Mean detection thresholds and standard deviations for each condition with gains ≤ 1 (***: p < 0.001, ** p < 0.01, *: p > 0.05).

to calculate the participants' detection threshold only based on the last 5 trials of each staircase pair, as it can be assumed that the staircases developed in the direction of the participant's true detection threshold until then. In contrast to using the reversal points only, as done by Ogawa et al. [192], this approach also has the advantage that all thresholds are based on the same number of data points. Moreover, it ensures that all analyzed data is collected within the same time range during the experiment, and, therefore, it can be assumed that participants were similarly concentrated and used to the task.

We analyzed the averaged thresholds with a two-way repeated-measures ANOVA. The normality assumption was verified with a Kolmogorov-Smirnov test as well as a visual inspection of the histogram and Q-Q plot of residuals. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

We found a statistically significant main effect of movement direction on detection thresholds ($F(5, 95) = 17.132, p < .001, \eta_p^2 = .474$). Post-hoc tests using the Bonferroni correction revealed significant differences between opposing movements along all axes, i.e., inward and outward ($p = .039$), upward and downward ($p = .001$) as well as forward and backward ($p = .002$) (see Figure 5.6). Furthermore, the detection thresholds differed significantly between *inward* and *forward* ($p = .002$), *outward* and *upward* ($p < .001$), *outward*

Table 5.1: Mean detection thresholds and standard deviations for each condition for decelerated hand movements. *DT* is the proposed detection threshold for every movement direction after averaging the means of both hands.

Movement Direction	Hand	M	SD	DT
inward	dominant	.603	.137	**.618**
	non-dominant	.633	.167	
outward	dominant	.566	.134	**.552**
	non-dominant	.538	.139	
upward	dominant	.711	.149	**.690**
	non-dominant	.669	.120	
downward	dominant	.598	.130	**.578**
	non-dominant	.558	.119	
forward	dominant	.748	.131	**.727**
	non-dominant	.705	.124	
backward	dominant	.592	.132	**.597**
	non-dominant	.603	.127	

and *forward* ($p < .001$), *upward* and *backward* ($p = .024$), and *downward* and *forward* ($p < .001$). We could neither find a significant main effect of the used hand on detection thresholds ($F(1, 19) = 4, 071, p = .058, \eta_p^2 = .176$) nor a significant interaction between hand and movement direction ($F(3.034, 57.642) = 4, 071, p = .063, \eta_p^2 = .119$). The derived detection thresholds for each motion direction are summarized in Table 5.1.

Based on the chosen staircase design, it is not only possible to compute a mean threshold for each participant but also to observe potential uncertainties of participants when deciding on whether a specific redirection feels natural or not. A high uncertainty would be reflected in large differences between a staircase's reversal points, which eventually results in a large within-subject variance measured for every single threshold. To analyze the participants' uncertainty, we computed a standard deviation based on the last 5 trials of each pair of staircases. The resulting values were aggregated across all conditions and participants, yielding an overall average standard deviation of $SD = .089$.

Moreover, we calculated mean detection thresholds over all conditions to analyze correlations with independent variables based on Pearson's r. We analyzed correlations with *Age* ($r = -.25$), perceived *Uncertainty* as stated by the participants (agreement to the statement *I was sure of my answer in most cases*) ($r = .27$), *Arm Length* ($r = .21$), experience with *HMDs* ($r = -.27$), and experience with *Hand Tracking* ($r = -.11$), but only found small to moderate correlations.

We measured simulator sickness using Kennedy's SSQ. Due to a technical error, the data for item *Difficulty Concentrating* is missing. The mean scores increased from 81.53 ($SD = 11.09$) before the experiment to 93.50 ($SD = 15.10$) after the experiment.

The AEQ revealed a medium to high average *Embodiment* score of 4.81 ($SD = 3.39$) on a scale from 1 to 7. The subscales *Appearance* ($M = 4.63$, $SD = 3.20$), *Response* ($M = 4.83$, $SD = 2.83$), *Ownership* ($M = 5.67$, $SD = 3.66$), and *Multisensory* ($M = 5.33$, $SD = 3.88$) revealed an especially high value for *Ownership*.

5.4.7 Discussion

The experiment results indicate that unnoticeable hand redirection in the form of decelerated movements is complex, as it depends on multiple factors, such as the motion direction and axis. In the following, we discuss the findings and put them into the context of related research.

5.4.7.1 Detection Thresholds

We found detection thresholds for decelerated motions in the range of [.552, .727] which is in a similar magnitude but slightly lower than the reported values by Zenner and Krüger [284] (.88) and Esmaeili et al. [65] [.669, .809] for a no-distraction scenario. Our values correspond to an offset between the real and virtual hand of about 7.5 cm to 16.2 cm after a motion of 20 cm of the virtual hand. The condition in our experiment that is most comparable to the setup of Zenner and Krüger is *forward*. Here, we found a detection threshold of .727, which is similar to their findings. The difference might be explained by the different distances between start and target. While in our setup they were 20 cm apart, in their setup it was 30 cm. So the same gain factor leads to a larger offset between the actual and virtual hand in their scenario, which might be more easily noticeable.

Esmaeili et al. [65] found a detection threshold of .809 for *horizontal* movements, which is closest to our conditions *inward* (.618) and *outward* (.552), a value of .869 for *vertical* movements, which corresponds to our conditions *upward* (.690) and *downward* (.578), and a threshold of .780 for their *depth* condition, which is similar to our conditions *forward* (.727) and *backward* (.597). As the participants in their experiment were allowed to move their hands freely, it is likely that the motions were larger than in our setup, which might explain the higher values. Furthermore, despite the unrestricted movements, Esmaeili et al. applied redirection to only one dimension at a time [65]. Therefore, the two unaltered motion axes may have served as reference values. This is different from our experimental task, where participants were required to always move their hands along the axis to which a redirection was applied. In direct comparison to two unaltered motion axes, the altered one might be more easily recognizable, leading to an increased sensitivity and higher thresholds for gains < 1 compared to our findings.

The staircase method we used makes it possible to analyze differences between participants. We found relatively large dispersion in each condition, ranging from $SD = .119$ to .149. This indicates that detection thresholds are individually different and should be determined for each person if possible. However, our data provide the opportunity to estimate lower-bound detection thresholds. Based on means and standard deviations, detection thresholds covering a certain proportion of the population can be derived.

To gain insights into what might have caused these individual differences of sensibility towards redirection, we analyzed the correlation between mean detection thresholds and different factors but found no significant effect.

5.4.7.2 Differences for movement direction

We found different detection thresholds on all three spatial axes. Sensitivity for redirection into one direction of each axis was significantly higher compared to the other motion direction on that axis, so we accept **H1**. On the vertical axis, we found a significantly higher detection threshold for upward movements than for downward movements (.69 and .578), meaning redirections were more easily noticed when moving the hand upwards. This difference may be caused by the additional physical effort users had to invest to elevate their arms compared to lowering them. Praveena et al. [207] have shown that in the teleoperation of robotic arms via a user's arm movement, weight can be communicated by a non-isomorphic mapping between robot and arm. A similar effect might cause the increased sensibility for upward motion compared to downward motion in our findings. The deceleration of hand movements could have been interpreted as additional weight in the upward movement, and, thus, the motion might have been perceived as more demanding, making participants more sensitive to the redirection.

Interestingly, for the horizontal axis, we also found a significant difference, but this effect appears to be contrary to the findings of Ogawa et al. [192]. While they report a higher sensibility for motions away from the center of the body, in our experiment, thresholds were higher for the inward direction compared to outward movements (.618 and .552). Ogawa et al. [192] hypothesized that the observed effect might be caused by different muscle feedback depending on the movement direction. However, we did not observe such differences in the flexion and extension of the user's arm for inward movements in comparison to outward movements. In both movement directions, the arm got increasingly extended with growing distance to the midline of the body. While the different setups, in particular the difference between angular shifts and translational gains, might contribute to the diverging results, we primarily attribute the observed significant effect to the fact that humans are highly trained to interact with their hands directly in front of their bodies. Therefore, redirections towards the body midline may be noticed more easily than lateral redirected movements.

Detection thresholds on the depth axis also differed significantly between both motion directions. For forward motions, we found a larger detection threshold than for backward motions (.727 and .597), showing a higher sensibility when moving the hand away from the body. In contrast to the horizontal axis, an increasing extension of the arm is inherent to forward movements, and, consequently, users receive different muscle feedback for forward and backward movements. In particular, decelerated movements away from the body required study participants to extend their arms completely, which was conflicting with the visual state of their virtual arm that was still flexed. Moreover, pointing and reaching movements might be usually performed with a higher concentration on the movement in comparison to backward motions. So in these cases, the proprioceptive cues might be more reliable and thus weaken the visual dominance effect.

5.4.7.3 Handedness (H2) and Manipulation Modes

We were unable to find a significant difference between the dominant and non-dominant hand, so we reject **H2**. There appears to be a trend towards a higher sensibility for the dominant hand in most conditions, but this needs to be further investigated in future studies.

Additionally, we analyzed the *accelerated* hand movements, which we included to prevent adaptation to the *decelerated* mode, as discussed in Section 5.4.2. As we had to narrow the range of possible gains to $[1, 1.6]$, we expected to observe some kind of ceiling effect because recent research reported detection thresholds close to the upper value. We observed an accumulation of data points close to 1.6, which prevented statistical analyses of *accelerated* hand movements. Therefore, the data we gathered on accelerated hand movements was not suitable to draw any conclusions.

5.5 Confirmation Study: Usage in Health Applications

To verify the derived detection thresholds, we conducted a confirmatory study in the context of a playful application, that was developed in a therapeutic context.

5.5.1 Participants

We invited three younger adults (P_1-P_3, mean age $M = 24$, $SD = 2.0$, all female) and three older adults (P_4-P_6, mean age $M = 66.3$, $SD = .577$, two female, one male). None of them participated in the previous experiment, and all were unaware of our research question. One participant wore glasses or contact lenses during the study. The three younger adults studied technical courses, while two of the older adults worked as gardeners and one as a primary school teacher. All participants, except for one younger adult, had used an Oculus Quest before. Two participants had used hand tracking with articulated fingers before. One younger adult had a light form of astigmatism. Beyond that, no vision disorders, such as color blindness or impaired stereovision, were reported.

5.5.2 Procedure

For the confirmatory study, we developed a game where soap bubbles have to be touched to free butterflies from inside the bubbles. In this playful approach, the participants were located on a tropical island. The Oculus Quest or Oculus Quest 2 with hand tracking was used in standalone mode. Different from the first study, the participants were represented without an avatar, but only their hands were displayed. Blue and orange soap bubbles were successively spawned in front of them, following the same positions as used in the first study. Blue bubbles could only be popped with the left hand, which was colored in the same shade, while orange bubbles only reacted to the right (orange) hand. When the soap bubble was touched correctly, it disappeared, and a butterfly was freed, which flew

Figure 5.7: The player's hand is following a butterfly.

towards the spawning position of the next bubble (see Figure 5.7). This indicated where the participants had to move their hands next and encouraged them to follow a straight path. There were always three bubbles spawned per trial, all on the same side of the body: The first bubble indicated the starting position, the second bubble the target position, and the third one moved the hand back to a resting position, preventing the participant from accidentally touching the next bubble. Then, the sides were switched.

While moving their hands from the first towards the second bubble, the gain was applied. Depending on motion direction, the gain was equal to the derived detection thresholds from the first experiment. Redirection was reset during the next trial when the participants were focused on their other hand. In a within-subjects design, the participants played two versions of the game. They were informed that we were investigating perception in VR and were instructed how to play the game. First, participants completed the version without redirection and then the redirected hands version. All six directions (upward, downward, outward, inward, forward, and backward) were repeated twice per hand, resulting in 24 trials per game. Participants spent about 5–10 minutes in VR. Between the two conditions, they were asked whether they noticed something unusual. After the second condition, they answered the following questions:

- Did you notice something unusual?
- Did you notice any differences during the second game? Which ones?
- Did you feel like the virtual hands were your own hands? Was this feeling different in the second game?
- Did it feel like your virtual hands were at the same location as your real hands? Was this feeling different in the second game?

5.5.3 Results

After the first condition, without redirection, none of the participants noticed anything related to the virtual hands.

After the second condition, five participants again did not notice anything related to the hand redirection. Only P_4 noticed that this time, the hands were "not synchronous". When asked about differences compared to the first round, P_2 reported harder reachability of the bubbles and hypothesized that the bubbles had been a little further away in the second version of the game. P_4 again reported that the hands felt different. Regarding embodiment, five participants reported that their virtual hands felt like their hands and that they were in the same position as their hands during both games. P_4 reported that their hands felt like their own in the first game but not during the second game. Interestingly, P_1 reported that their hands felt more like their own during the second game with redirection.

5.5.4 Discussion

Overall, five out of the six participants did not notice the hand redirection, indicating that the generalized detection thresholds may apply to a broader user base of VR applications. Further studies are necessary to confirm these first indications, as the sample was limited to only 6 participants in the second study.

Besides this general impression on the applicability of our detection thresholds, we could gain valuable insights on the possible limitations of generalized hand redirections. In particular, the older adult P_4, who was the only one that consciously noticed the redirection, reported previous experience with VR and hand tracking. In a follow-up interview, they mentioned being familiar with the concept of redirected walking. Although their last time using redirected walking was more than 18 months ago, just knowing about the concept of redirection in VR might have increased their sensitivity. Interestingly, P_2 reported harder reachability in the redirected condition but stated that their virtual hands were in the same positions as their hands during both games. They did also report knowing about redirected walking but had never tried it. All other participants were not familiar with the concept of redirection in VR and had no experience with hand tracking. So those factors might affect redirection sensitivity.

In summary, in this short study, most participants did not notice hand redirection with the gains derived in the first experiment. The effects of hand tracking experience and a more in-depth knowledge of VR interaction techniques on redirection sensitivity should be researched in future studies.

5.6 Limitations

In this work, we focused on estimating detection thresholds for decelerated hand movements (i.e., gain factors ≤ 1.0) to be applied in therapeutic applications. Since we only recruited healthy participants for the experiment, the findings have to be confirmed in a clinical evaluation.

Furthermore, detection thresholds for hand redirection seem to depend on the range of motion. While we focused on a fixed movement length of 20 cm and predefined starting and target points, future studies could extend this setup to different layouts.

Finally, although we aimed for a realistic rendering of the hands, the appearance could be further improved by using scans of the users' hands.

5.7 Conclusion

In this work, we presented a gain-based hand redirection method for full-body avatars to gather insights into redirected hand movements during midair interaction. Answering **RQ1.2**, the data collected during a psychophysical experiment indicates that detection thresholds differ significantly depending on the direction of performed movements. In contrast, no significant differences between the dominant and non-dominant hands of users could be found. Based on these results, we report threshold estimates for both directions on all three spatial axes. Furthermore, we observed interpersonal differences for hand redirection sensitivity and, therefore, suggest that more accurate, personal thresholds could be determined in an individual calibration procedure. Nevertheless, as we also found a rather high uncertainty of study participants as measured by the standard deviation of detection thresholds, we hypothesize that our threshold estimates apply to a large proportion of the population.

To obtain first insights on that hypothesis, we conducted a confirmatory study. We applied the generalized detection thresholds to hand movements in a playful application, which was developed in a therapeutic context. Only one of the six study participants noticed the offset between the real and virtual hand positions. Moreover, the participant who noticed the redirection reported prior knowledge on VR interaction techniques in general as well as redirected walking and, therefore, might be more sensitive to hand redirection. For the usage in VR rehabilitation, follow-up experiments targeting older adults as well as users with movement restriction of the upper extremities or pain patients could indicate whether the observed detection thresholds can be transferred to other user groups or if they have to be adapted accordingly.

5.8 Future Work

From the observations in both the psychophysical experiment and the confirmatory study, several research questions for future studies arise. Firstly, it is an open question of how our derived values can be applied to bimanual interactions. In the context of haptic retargeting, Gonzalez and Follmer [88] have recently shown that users are more sensitive when retargeting is applied in different directions on both hands. Therefore, the question arises of how this effect correlates with our identified axis-dependent detection thresholds.

Another issue that is inherent to hand redirection when varying gains are applied to different movement axes and directions is an increasing drift of the virtual hands over time. To reset the hand position, approaches like the blink-suppressed hand redirection method recently proposed by Zenner et al. [285] could be applied.

Regarding the experiment design, our setup was suitable to investigate decelerated hand movements, which are particularly valuable for therapeutic applications. Although we additionally collected data on accelerated hand movements, they did not reveal any insights except for the too narrow range of tested gains. In future studies, detection thresholds of accelerated hand movements could be investigated with an adapted experimental setup.

Finally, dedicated user studies are necessary to answer the question of whether and to what extent decelerated hand movements are effective for upper limb therapy. We speculate users might be encouraged to perform larger movements than they would do without such redirection, which might improve therapeutic outcomes. This has to be investigated in a clinically controlled setup.

In the next chapter, we further investigate hand redirection sensitivity with a special focus on the appearance of the virtual hand, which has been reported to affect redirection sensitivity in a specific scenario for angular redirection [193]. While our results in Chapter 4 did not show an effect of hand appearance on agency, there is clear evidence for an effect on SoE, especially on SoO [8, 132, 133, 146, 157, 162, 193, 287]. However, whether avatar appearance also affects redirection sensitivity for gain-based hand redirection remains an open question. We contribute to this question by analyzing detection thresholds for four different virtual hand models (abstract, block hand, artificial hand, and realistic hand) using a psychometric curve approach.

6

The Impact of Virtual Hand Appearance on Embodiment and Redirection Sensitivity

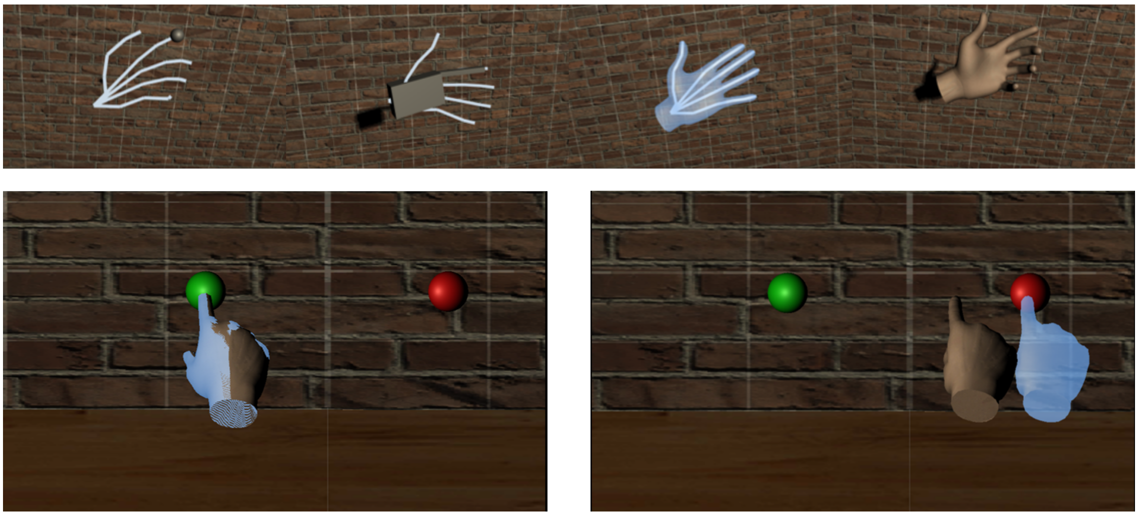


Figure 6.1: We tested redirection sensitivity and embodiment for four hand models in a Fitts's law-inspired task. Top: Sphere hand, Block hand, Artificial hand and Realistic hand. The blue skeleton shows the participant's tracked hand and was not visible during the experiment. Bottom: Redirection task with decelerated redirection applied. Here, the blue hand visualizes the participants' real hand and was not visible during the experiment.

In this chapter, we further investigate the effect of hand appearance on embodiment and redirection sensitivity using four virtual hand models with different levels of realism and anthropomorphism. This chapter investigates **RQ1.3** and is based on the following publication:

> J. Hartfill, M. Schrader, and F. Steinicke. "Investigating the Impact of Virtual Hand Realism on Embodiment and Redirection Sensitivity in Virtual Reality". In: *GI VR / AR Workshop*. Gesellschaft für Informatik e.V.. Germany, 2024. DOI: 10.18420/vrar2024_0016

6.1 Introduction

Previous research has explored the embodiment of virtual hands and the general concept of redirection sensitivity in VR. However, there is a lack of focused research on how different virtual hand representations impact users' sensitivity to redirection.

In this work, we focus on two aspects of virtual hand appearance: realism and anthropomoroshim.

We hypothesize that:

- Different virtual hand appearances will significantly affect the sense of embodiment experienced by users.
- Detection thresholds for redirection sensitivity will vary across different virtual hand models.

We conducted an experiment with twenty-nine participants, who performed reaching tasks in a VE. Four different hand models (*Sphere*, *block*, *Artificial*, and *Realistic*) were tested using varying redirection amounts.

This work is structured as follows: In Section 6.2, the gain-based hand redirection method used in this work is introduced. Section 6.3 describes the experiment that was conducted to evaluate embodiment and redirection sensitivity for four different virtual hand models. In Section 6.4, we describe the data analysis procedure and report our findings. The results are discussed in Section 6.5, and the limitations of this work and possible future work are briefly summarized in Section 6.6. Section 6.7 gives a short summary and concludes the work.

In this work we further investigate the effect of hand appearance on embodiment and redirection sensitivity. We contribute (1) to the more profound understanding of the relation between virtual hand appearance and embodiment, with a focus on different DoFs and visual appearances, and (2) the potential effect of hand appearance on redirection sensitivity for accelerated and decelerated movements. A linear gain-based redirection method for hand tracking was implemented in this work, similar to the gain-based methods in [65, 108, 284], which is introduced in the following.

6.2 Hand Redirection Method—An Update

We implemented a redirection method similar to [108]. However, initial tests revealed an issue for hand movements from the wrist: If the fingertip is moved from the wrist only, leaving the hand root bone steady, no redirection was applied to the fingertip.

Since in our work the fingertip is a crucial part for doing the reaching task, especially because one of the hand representations is only a small Sphere where the fingertip is, we adjusted the algorithm to work for the fingertip.

Instead of calculating the redirection amount based on the root bone, the movement of the fingertip is used in our approach. That redirection amount is then added to the root bone of the virtual hand. Thus, the whole virtual hand is shifted depending on the position of the index finger.

To calculate the x-component of the virtual hands' root bone position, V_x the following formula was used:

$$V_x = R_x + (T_x - O_x) * (g - 1)$$

with R_x being the x-component of the real hands' wrist position, the x-component of the real hand fingertip position T_x, the x-component of the starting point of the redirection O_x and the gain factor g.

This method ensures the virtual hand matches the real hand's position when the fingertip is at the starting point, preventing immediate jumps. Figure 6.2 shows that the tracked hand in light blue and the virtual hand are in the same position as long as the index fingertip is inside the starting position. A drawback is that moving the index finger along the x-axis while the wrist remains fixed causes the whole virtual hand to shift sideways. As demonstrated in Figure 6.2, the virtual hand shifts even though the wrist's position is constant. However, this effect was minor and not noticeable to participants during VR scene testing. No feedback indicated awareness of this issue.

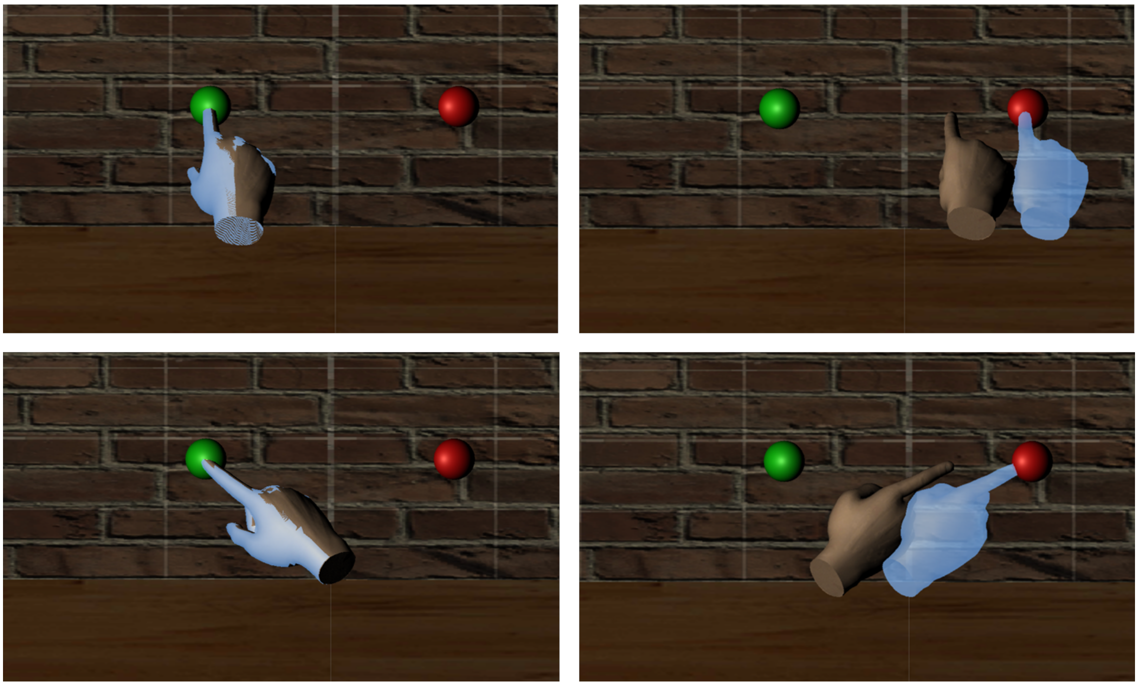


Figure 6.2: Offset between the virtual hand and the real tracked hand (light blue). The tracked hand was not visible to the participants. The green sphere is the starting point; the red sphere is the target.
Top: Offset between the hands in a perpendicular orientation to the x-axis. Bottom: Offset between the hands when they are tilted.

We applied the redirection only to the horizontal axis to ensure separation of conditions from one another. The y and z components of the virtual hand's position were identical to those of the real hand.

6.3 Study

We conducted an experiment to investigate accelerated and decelerated hand movements in VR using four different hand representations. Participants performed vertical movements with the right hand, from left to right or from right to left, with different gains or no gain applied. After each trial, they were asked to choose if the virtual hand was faster or slower than their real hand (even if it was identical). We derived detection thresholds for each hand representation using a psychometric curve approach.

6.3.1 Overview

The effect of the virtual hand model on the SoE is not clear yet. Especially the influence of varying intermediate DoFs (e.g., partial finger movement) on the feeling of embodiment has not been comprehensively examined. Most studies contrast static models with fully articulated hands, leaving a lack of understanding about the nuanced effects of partial articulation on the SoE.

In another line of research, the effect of hand appearance on redirection sensitivity has been investigated. To the best of our knowledge, there is only one study investigating the effect of two levels of hand realism on redirection sensitivity. We want to deepen the understanding of this effect by incorporating more levels of hand realism and using a different hand redirection method.

In summary, our hypotheses are **H1**: Sense of embodiment increases with higher virtual hand realism. **H2**: Redirection sensitivity increases with higher virtual hand realism.

6.3.2 Materials

In this study, we investigated four different hand models: *Sphere*, *Block*, *Artificial*, and *Realistic*, see Figure 6.1), that were all operated with hand-tracking technology and provided different levels of realism in terms of appearance and dexterity. The most simple and abstract hand model, *Sphere*, was inspired by the artificial hand model used by Esmaeili et al. [65]. We used a gray Sphere of approximately 2 cm radius to visualize the user's fingertip of the index finger, as can be seen in 6.1, top left. Please note that the skeleton hand shows the user's actual hand pose and was invisible to the user during the study. This hand does not have any movable joints. The hand model *Block* consists of a brown block that represents the user's palm with a thinner block attached that moves with the fingertip position of the user. The model gives the user some feedback on the overall pointing direction of the hand and also provides some inner-hand movement between the palm and fingertip. *Artificial* and *Realistic* both have an anthropomorphic layout with five fingers and provide full hand dexterity within the scope of the hand-tracking capability of the used hardware. The *Artificial* one uses a bluish, semitransparent texture. Translucent hands do not occlude the object of interest, which can make it easier to interact with the environment. For the *Realistic* hand, we chose a skin texture.

Reaching tasks were done with the right hand, regardless of handedness, similar to Zenner and Kruger [284], Ogawa et al. [192] and Esmaeili et al. [65]. A difference in redirection sensitivity depending on handedness was not found by [108]. Movements were performed on the horizontal axis either from left to right or from right to left. We investigated 13 gain factors between 0.7 to 1.3 in increments of 0.05. A gain factor of 1.3 increased the movement of the virtual hand by 30% relative to the starting point. Conversely, a gain factor of 0.7 decreased the movement of the virtual hand by 30%.

6.3.3 Methods

Four hand models were tested in two movement directions (left and right), resulting in a total of eight conditions. Each of the 13 gain factors was tested twice per condition, resulting in (8 conditions * 13 gain factors * 2 repetitions =) 208 trials. The order of conditions was counterbalanced. Participants completed trials first from left to right and then in the other direction for each hand model.

The VR scene was built in Unity and run on an Oculus Quest 2 in standalone mode. Participants were immersed in an empty room with a marker at the center indicating their position (see Figure 6.3).

For each trial, a sphere appeared in front of the participants. After touching the start sphere, it turned green to show it had been successfully touched, and after 0.5 seconds, it disappeared. Then a red sphere appeared at the target location. Touching this sphere also turned it green, and it appeared after 0.5 seconds.

When the target sphere was touched, a virtual screen appeared, showing the question "Was your virtual hand faster or slower than the movement of your real hand?" and two answer buttons for faster and slower. The position of the buttons switched after each trial to avoid any bias due to a preference for the right or left button. The answer buttons were operated using the left hand. Firstly, this gave the participants the opportunity to rest their right arm, and secondly, this way it was possible to reset the offset between the real and virtual hand before the next trial without the participants noticing. To the right, a larger panel showed brief instructions for the study.

The start and target spheres were located roughly in front of the participants' shoulders, with a distance of 50 cm, and had a diameter of 2.5 cm. The distance between the spheres was 30 cm. With the most extreme gain factors (.7 and 1.3) applied, this resulted in an offset of 9 cm between the real and virtual hand.

The gain-based redirection was applied as soon as the participants touched the start sphere. When touching the target sphere, the gain-based redirection was stopped, but the resulting offset between the real and virtual hand was not reset yet.

6.3.4 Procedure

The study was conducted remotely during the Covid-19 pandemic. Participants borrowed the necessary hardware (Oculus Quest 2) and participated from home. Detailed written instructions were given on the setup and information on how to conduct the study. Additionally, participants had the opportunity to contact the researchers while performing the study.

After giving informed consent, participants were asked to answer a demographic questionnaire and the SSQ [215] for a baseline value. Participants then experienced four blocks of VR, one for each hand model. After each block, the SSQ and Avatar Embodiment Questionnaire (AEQ) [197] were collected.

At the beginning of each block, participants had the opportunity to get familiar with the respective hand model and could practice the task. Whenever they felt ready, they started the actual trials by touching a white Sphere.

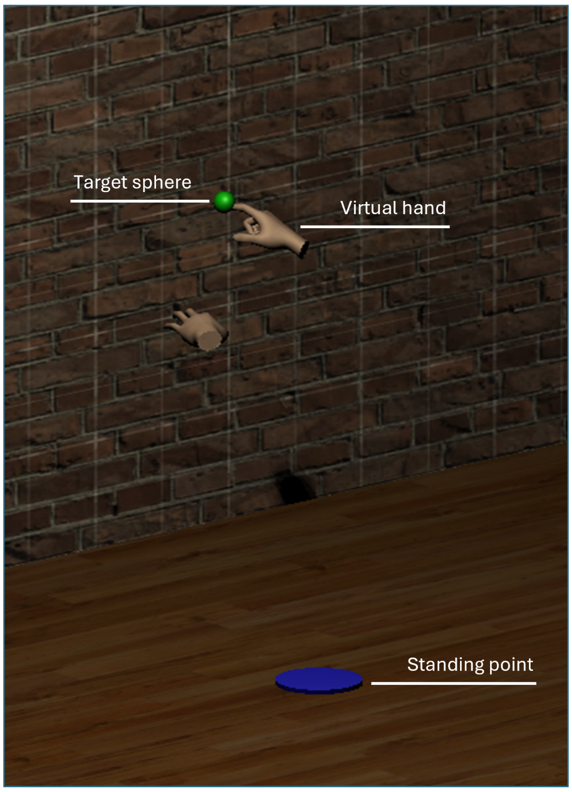


Figure 6.3: Third-person view of experimental setup. The participant stands in the blue circle and is embodied with two hands. The right hand completes the reaching task towards the green sphere, while the left is used to operate the question panel after each trial.

6.3.5 Participants

29 people participated in this study; 19 self-identified as female and 10 as male. Age ranged from 18 to 65 (M = 25.9, SD = 8.2 years). The majority of them were students

or employees in the field of HCI. Twelve participants reported using glasses for vision correction, and four used contact lenses. No one reported having an eye disorder or displacement of equilibrium. All participants stated to have used a VR HMD before, with 16 of them having experience with hand tracking.

6.4 Analysis and Results

In this section, we first analyze the Embodiment data. Then we summarize the psychometric curve procedure and analyze the detection threshold data.

6.4.1 Avatar Embodiment Questionnaire

The AEQ [197] consists of four subscales (Appearance, Response, Ownership and Multisensory) that together form the final Embodiment Score. For each score, we conducted a repeated measures ANOVA and performed a Shapiro-Wilk test on the residuals to ensure the normality assumption. When the ANOVA indicated a significant effect, we performed pairwise post-hoc tests using Bonferroni correction.

For the sub-scales, we found significant effects only on the Ownership subscale ($F(3, 112) = 13, 68, p < .001, \eta_p^2 = 0.268$), see Figure 6.4. Post-hoc tests revealed significant differences between *Sphere* and *Artificial*, *Sphere* and *Realistic* as well as *Block* and *Artificial*, and *Block* and *Realistic* (all $p < .001$).

For the overall embodiment score, we found a statistically significant effect of hand model on SoE ($F(3, 84) = 15.766, p < .001, \eta_p^2 = 0.137$). Post-hoc tests revealed significant differences between *Sphere* and *Artificial*, *Sphere* and *Realistic* as well as *Block* and *Artificial*, and *Block* and *Realistic* (all $p < .001$), see Figure 6.5.

6.4.2 Detection Thresholds

We use a psychometric curve approach to investigate redirection sensitivity with different virtual hand models, analogous to [244] estimation of redirected walking thresholds. First, we plot the participants' proportions of answering *faster* against gain factors $.7 - .95$ and $1.05 - 1.3$. Gain factor 1 was excluded from the analysis, as none of the answer possibilities was correct for gain factor 1, and participants were forced to choose an answer, which could possibly lead to a bias in the data. Then we fit the psychometric sigmoid function $f(x) = \frac{1}{1+e^{-\frac{x-p_1}{p_2}}}$ by optimizing p_1 and p_2 for each hand model. The resulting plots can be seen in Figure 6.6. For each hand model, we retrieved the overall percentage of correct answers, which was quite high over all hand models, ranging from 79.96% for *Block* to 81.11% for *Artificial*. From the fitted functions, we retrieved the Point of Subjective Equality (PSE), which is the value at the 50% proportion of the answers, as well as detection threshold levels, the points of 25% and 75% proportion of answering "faster." The difference between the PSE and 25/75% point is the Just Noticeable Difference (JND), which we also calculated for each hand model and can be seen in Figure 6.6.

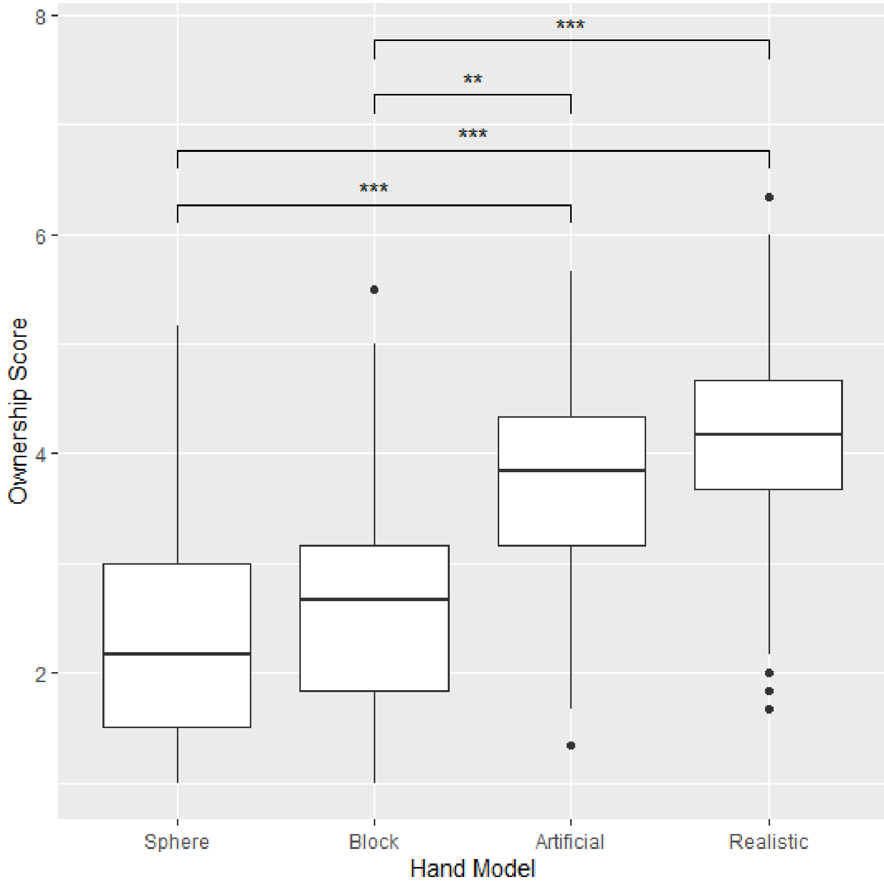


Figure 6.4: Ownership scores for each hand model. ***: p < 0.001, ** p < 0.01.

A multivariate ANOVA was performed to evaluate the effect of hand model (four levels), motion direction (inward or outward), and redirection mode (accelerated or decelerated) on redirection sensitivity. We transformed the data using Square Root Transformation. The sphericity assumption was met, but a Shapiro-Wilk test on the residuals indicated that the normality assumption was not met. However, the ANOVA is robust against small deviations of skewness and kurtosis ($\gamma_1 = .026$ and $\gamma_2 = -.363$) when the sphericity assumption is met, as was shown by [26].

The results indicated no significant main effect for hand model ($F(3, 84) = .111, p = .953, \eta_p^2 = .004$), no significant main effect for redirection mode ($F(1, 28) = .178, p = .676, \eta_p^2 = .006$) and a significant main effect for movement direction ($F(1, 28) = 20.213, p =< .001, \eta_p^2 = .419$). Regarding the interaction effects, only the interaction of movement direction and redirection mode was significant ($F(1, 28) = 6.132, p =< .020$).

Simple main effects analysis indicated that movement direction is significant for decelerated hand movements ($F(116, 116) = -4.52, p =< .001$), see Figure 6.7.

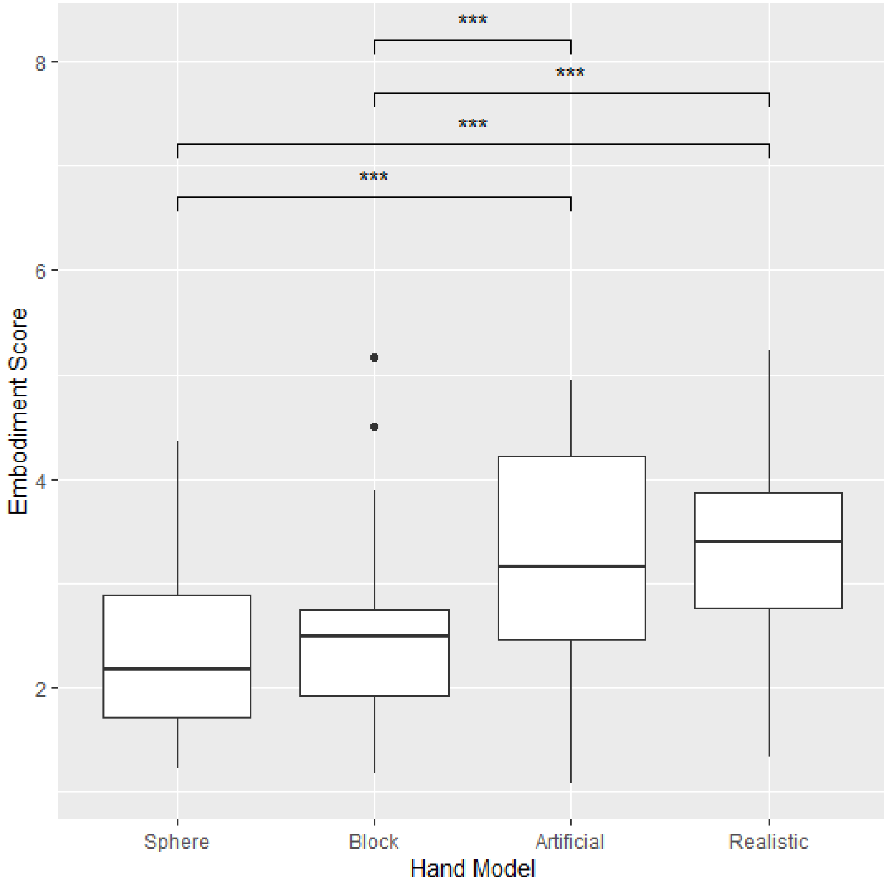


Figure 6.5: Embodiment scores for each hand model. ***: $p < 0.001$.

6.4.3 SSQ

Results of the SSQ increased from 2.0 ($SD = 3.3$) before the experiment to 9.9 ($SD = 11.8$) after. This is in line with the average total severity of 9.8 reported by Kennedy et al. [135].

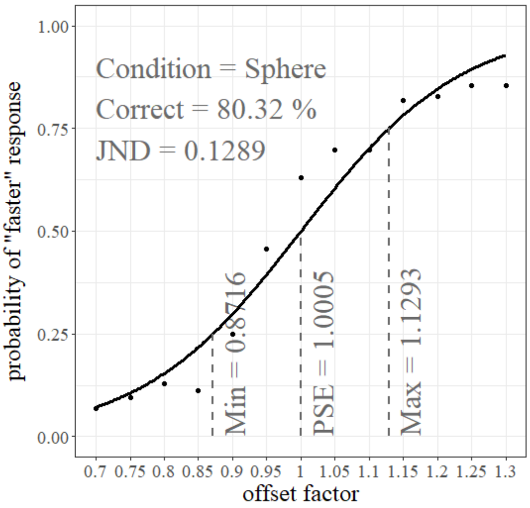
6.5 Discussion

In this section, we will discuss the results regarding embodiment and redirection sensitivity and connect the findings to the research questions.

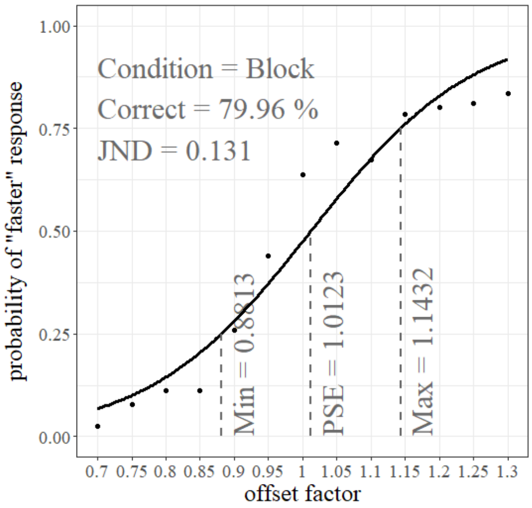
6.5.1 Embodiment

Our analysis of SoE towards the four different hand models revealed medium mean scores for embodiment, increasing from *Sphere* to *Realistic*. In particular, we found the abstract hand models (*Sphere* and *Block*) were significantly different from both anthropomorphic hand models (*Artificial* and *Realistic*), which partially confirms **H1**.

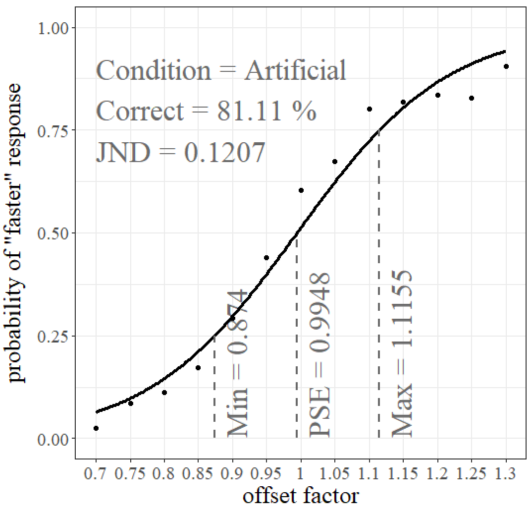
When analyzing the subscales of this questionnaire, we found that these significant effects were reflected in the *Ownership* subscale, while the other three subscales did not reveal significant differences between the hand models.



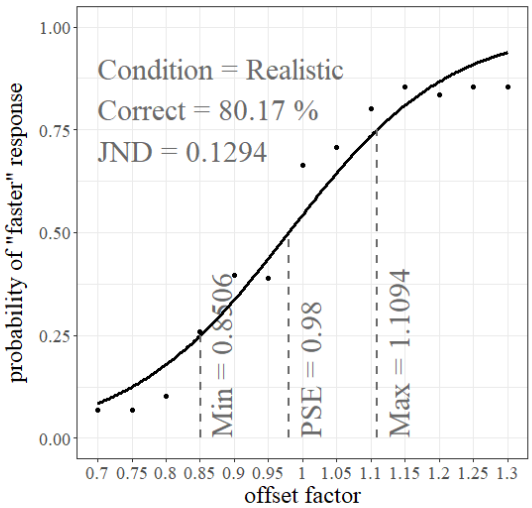
(a) *Sphere*



(b) *Block*



(c) *Artificial*



(d) *Realistic*

Figure 6.6: Psychometric curves for all hand models.

We could not find a significant difference between both anthropomorphic hand models with artificial and more realistic appearances, but significant differences between both anthropomorphic hand models to both non-anthropomorphic hand models. So dexterity seems to be an important factor for SoE. This is in line with findings in previous works [193, 286, 287], which reported significant effects of hand model realism on embodiment. Zhang et al. [286] interpret their findings to be related to the combination of hand tracking and fully articulated virtual hands. This is supported by our findings: Both anthropomorphic hand models resulted in higher embodiment ratings than the non-anthropomorphic hand models. Having a matching visualization for each finger seems to play a role in eliciting a feeling of embodiment towards virtual hands, even if the fingers are not necessary for the task.

We did not find a significant effect between the other two non-anthropomorphic hand

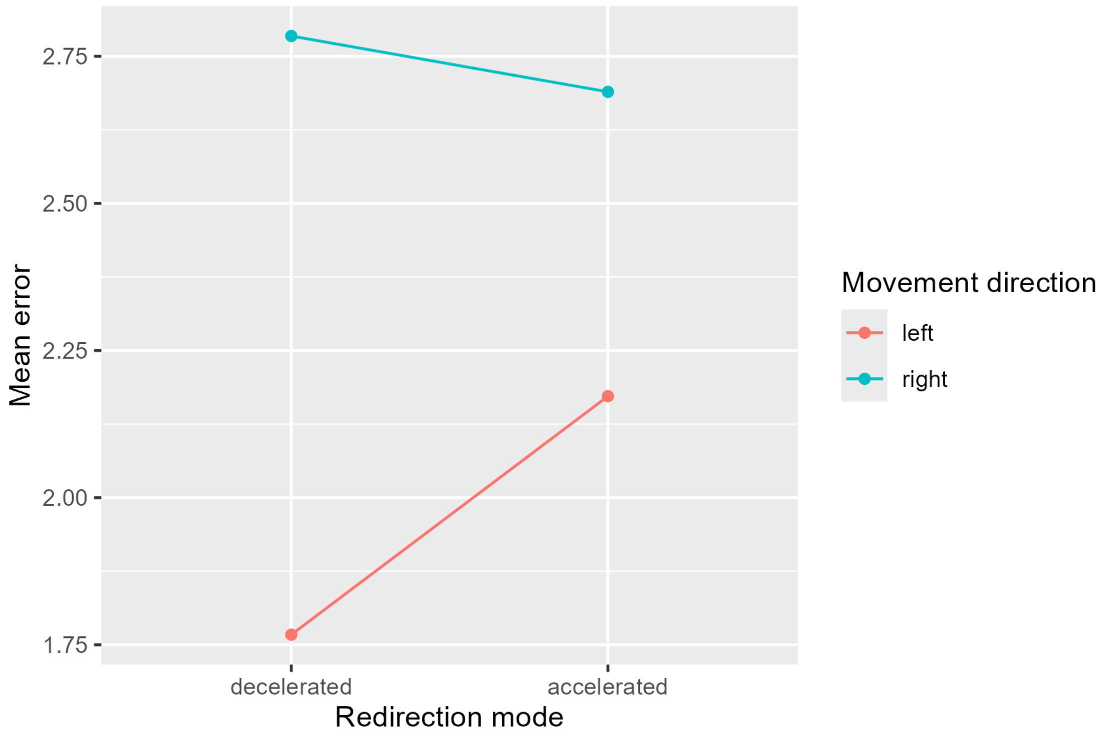


Figure 6.7: Simple main effects analysis for movement direction and redirection mode.

models in terms of embodiment, despite both having different levels of DoFs. Although both hand models appear to be quite different, with the Block hand being larger, visualizing not only the real hands' position but also the orientation, and additionally having a Block finger that moved, still the difference was not large enough in terms of SoE.

While other works from the field of virtual hand embodiment used tasks that were either set in a game context (like [157], [287], [113], [286]) or inspired by a real-world task ([8]), the task in this work is more abstract and simple. Possibly, the lack of context in our task might contribute to the fact that both anthropomorphic hand models did not evoke differences in SoE. Participants seem to have perceived both the artificial hand model and the more realistic one equally in terms of embodiment.

6.5.2 Redirection Sensitivity

We found that hand movement redirection stays unnoticed for gains between .8716 and 1.1293 (JND .1289) for *Sphere*, for gains between .8813 and 1.1432 (JND .131) for *Block*, for gains between .874 and 1.1155 (JND .1207) for *Artificial*, and for gains between .8506 and 1.1094 (JND .1294) for *Realistic*. This is in line with findings from Zenner et al. [284], who reported redirection between .88 and 1.07 for a no-distraction scenario to go unnoticed by the user. Also, Esmaeili et al. [65] reported detection thresholds in a similar range: .809 for decelerated movements and 1.310 on the horizontal plane, which corresponds closest to our setup. In the previous chapter (Chapter 5) we reported detection thresholds for decelerated hand movement on the corresponding axis of .618 for inward movements and .552 for outward movements [108].

In this work, our data again revealed a significant effect on movement direction. This is in line with our previous findings [108] of significantly different redirection sensitivity for all spatial axes, such as the horizontal axis, as in our setup. However, in Chapter 5 we only analyzed decelerated hand movements. In this work, we investigated both accelerated and decelerated hand movements and could only find an effect of movement direction for decelerated hand movements. This suggests that the findings for decelerated hand movements are not directly applicable for accelerated hand movements, as both redirection modes seem to be perceived fundamentally differently by the users. The effect might be related to the reachability of the target sphere in our setup. Participants had to reach a point in space with their right hand, that was up to 9 cm left of their left shoulder. This might have resulted in an uncomfortable, unusual, and thus noticeable movement.

We did not find any effect of hand appearance and DoFs on redirection sensitivity or any interaction effect of hand model with any of the other factors tested, which does not support **H2**. This contrasts with findings from Esmaeili et al. [65], who reported increased redirection sensitivity for a more realistic hand model when the hand is shifted to the left. In their work, they used a fully articulated realistic hand model and an abstract sphere, which are highly similar to *Realistic* and *Sphere* in this work. So the different findings do not seem to depend on hand realism in terms of visual appearance and DoFs. But the redirection techniques used are quite different. While we used a gain-based approach, Esmaeili et al. [65] used angular redirection. Participants in their study performed pointing movements away from the body and were redirected to the left or right (inward or outward). In our study, however, the hand was also redirected to the left or right, but on the same axis as the motion was performed. Still, the final offset when reaching the target sphere was up to 9 cm, depending on the applied gain in our work, and 10 cm in the work of Esmaeili et al. [65]. So although some points are similar, redirection technique and the type of movement seem to be important when investigating the influence of different hand models on redirection sensitivity.

While our data shows that the hand model influences the SoE, we did not find a similar trend for redirection sensitivity, indicating that the hand appearance, especially anthropomorphism, of the used hand model is less important in this context. Our results for embodiment are in a medium range, which might be caused by participants not paying much attention to the used hand model. This could be because they concentrated on the task, which was abstract and did not have a logical connection to the model of the virtual hand. Perhaps increasing the role of the hand model, for example, by adding a familiarization phase for each hand model or adjusting the surrounding context to fit each hand model, might increase the role of the hand model regarding redirection sensitivity.

To answer **RQ1.3**, we did not find an effect of hand appearance on redirection sensitivity, although we found an effect on SoE, suggesting that redirection sensitivity and SoE are independent of each other. Our findings suggest that the dexterity of the virtual hand is important for SoE, while for redirection sensitivity it appears that other factors than hand appearance might play a role.

6.6 Limitations and Future Work

While this study provides valuable insights into the impact of virtual hand realism on embodiment and redirection sensitivity in VR, several limitations should be acknowledged. Addressing these in future research will help deepen our understanding and improve the design of VR systems.

In this work, we maintained a fixed order for movement directions, starting with movements from left to right followed by right to left for each hand model. This may have contributed to the significant main effect for movement direction that we found by inducing a learning bias. Future studies should randomize the order of movement directions to ensure more reliable findings.

All tasks in this study were performed with the right hand, irrespective of participants' handedness. This approach might not accurately reflect the experiences of left-handed users or the nuances of bi-manual interactions in VR. Future research should include both hands and consider participants' handedness to provide a more comprehensive understanding of how handedness impacts embodiment and redirection sensitivity.

This study focused on hand movements on the horizontal axis only, limiting the generalizability of the results to other kinds of movements. Future research should investigate more diverse or complex movements to better understand how redirection sensitivity varies across different types of hand motions.

Moreover, the task in our work did not require any DoFs of the virtual hand, as we wanted to have the same task for all hand models and also include hand models without any DoFs. So different levels of control over the virtual hand were usable, but not necessary to solve the task. For future work, it would be insightful to use a task that requires some dexterity of the hand, like a simple grabbing task, and look into hand models with different DoFs that provide at least a grabbing motion.

6.7 Conclusion

This study aimed to explore the impact of virtual hand realism on SoE and redirection sensitivity in VR. We focused on four different virtual hand models: *Sphere*, *Block*, *Artificial*, and *Realistic*, with different degrees of dexterity and visual detail. Regarding embodiment, we found significant differences across the different virtual hand models. Specifically, the more anthropomorphic models (*Artificial* and *Realistic*) provided a significantly higher SoE, in particular Ownership, compared to the more abstract models (*Sphere* and *Block*). This aligns with previous research, showing that more realistic virtual hand models are crucial for enhancing users' SoE in VR. Redirection sensitivity, however, did not vary significantly between different hand models. This suggests that the degree of realism and dexterity of virtual hands has a less pronounced impact on the detection thresholds for hand redirection. We did find a significant interaction effect of movement direction and redirection mode on redirection sensitivity, showing that redirection sensitivity depends on complex factors.

In this work we included hand models that vary in terms of anthropomorphism (different numbers of digits (0, 1, 5) and different DoFs (0, 1, fully articulated)) and realism (2 levels for the fully articulated hands). However, truthfulness in these models never reached a personalized level, as we did adjust the virtual hands for each user. This is possible using scanning techniques, such as generating the model from videos or photos [184, 289]. However, to be able to use such hand models in a VE, some post-processing steps are necessary. In the following chapter, Chapter 7, we present a fast and easy approach for generating photorealistic and fully rigged hand models. Using a camera rig with 50 Raspberry Pi[1] cams [276], we can equip users with virtual versions of their hands in 30 minutes, using that pipeline.

[1] https://www.raspberrypi.com/documentation/accessories/camera.html

7

A Fast and Easy Pipeline for Generating Fully Articulated Photorealistic Virtual Hands

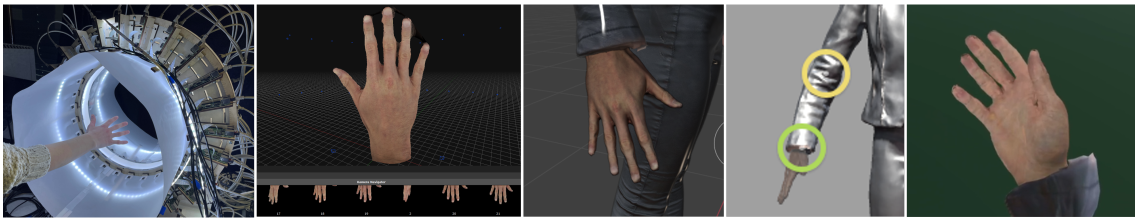


Figure 7.1: Our pipeline for photorealistic virtual hands consists of 5 main steps. From left to right: (i) Capturing photos of the real hand using the hand scanner, (ii) Using a photogrammetry software like 3DF Zephyr to reconstruct the model, (iii) Preparing the model for rigging, (iv) Rigging the avatar in Mixamo, and (v) Importing the fully articulated hand models in Unity.

This chapter presents a pipeline to include fully articulated, photorealistic hand scans of the user in VR applications with hand tracking. This is done by capturing photos of the hand from different perspectives simultaneously using a customized hand scanner. Then, using open-source photogrammetry software, a rigged 3D model of the hand is created and integrated into a Unity application, ready to use with the Meta XR Interaction SDK. We present guidelines on how to get from a set of 2D images to a fully articulated, personalized virtual hand model within 30 minutes. This chapter is based on the following pre-print:

J. Hartfill, T. Rolff, L. Kruse, S. Schmidt, and F. Steinicke. *Realism at Hand: A Fast and Easy Pipeline for Generating Fully Articulated Photorealistic Virtual Hands*. 2025. doi: 10.25592/uhhfdm.17705

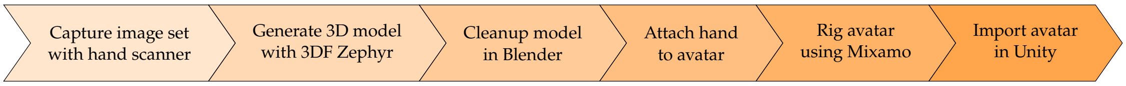


Figure 7.2: Procedure to generate a photorealistic virtual hand through our proposed pipeline.

7.1 Introduction

As the appearance of virtual hands plays an important role when embodying an avatar [8, 132, 133, 146, 157, 162, 193, 287], having a photorealistic representation of one's hands in VR may further improve the illusion [113]. Recently, machine learning approaches to creating photorealistic hands have been the focus of several research projects. Mundra et al. [187] developed a model to render photorealistic hand textures in real time, based on training a neural radiance field (NeRF) along with mesh-guided sampling. Their approach results in 45 frames per second (FPS) with an NVIDIA GeForce RTX 3090, therefore requiring more computational power than most standalone VR HMDs are capable of. In a different pipeline by Moon et al. [184], the authors use a phone scan of a user's hand to create an animatable hand avatar within two hours. Nevertheless, adapting these to be used in VR applications requires additional steps such as rigging the 3D meshes. As such, to the best of our knowledge, there is no documented pipeline readily available for capturing a photorealistic 3D model of one's hand and utilizing it within the VE.
To address this, we propose a pipeline for capturing photorealistic scans of human hands that results in accurate 3D representations; see Figure 7.2. We focus on a pipeline that is low-cost and requires a minimum of 3D modeling or computer science knowledge. To summarize, we provide the following contributions:

- a detailed overview of a simple hand scanner pipeline, and
- recommendations for easy-to-use, free software for virtual model reconstruction from 2D images and avatar creation for Unity.

7.2 Hand Generation Pipeline

In this section, we introduce our pipeline for generating realistic 3D hand models to be used in Unity.

7.2.1 Hand Scanner

Our work is based on the hand scanner published by Yang et al. [276]. In their work, they deploy 50 Raspberry Pi's (RPi)[1], each equipped with an RPi camera module 2 for image acquisition. For our scanner, the RPis are mounted onto a custom-crafted wooden rack consisting of two rings (see Figure 7.1, left). This setup allows us to capture all images at the same time, avoiding the need to hold the hand still for several seconds.

[1] https://www.raspberrypi.com/

7.2.2 Virtual Hand Generation

After the set of hand photos is taken, the images are masked using Segment Anything[2] (SAM) [141]. Here, the SAM web UI[3] is used, masking out the background of the hand scanner. The user is required to click on the hand in each image, resulting in pixel-accurate masks. This ensures that only the hand is reconstructed during the process, without additional parts of the background. For reconstructing the 3D hand model from the image set, we utilize 3DF Zephyr[4]. We use the default settings of Zephyr for body parts, resulting in a high-quality 3D textured model. To clean up some incoherently scanned parts of the model, we perform a cleanup step in Blender[5], removing wrongly reconstructed parts of the model and closing possible holes utilizing the Mesh Repair Tools extension[6]. Afterward, we smooth out the 3D mesh, reducing the noise generated during the reconstruction.

To provide a seamless hand-tracking experience, we generate a rig for the hand using Mixamo[7] by Adobe. As Mixamo does not support single limbs, we attach the 3D mesh onto a whole-body avatar in Blender, replacing their original hands. After processing the model with Mixamo, the full-body avatar can be downloaded with the generated rig. Depending on the application, the whole-body avatar can be imported into Unity, or the mesh for the remaining body can be deleted, only leaving the hands.

7.2.3 Integration into Unity

For easy hand tracking support in Unity, we use a Unity framework [81], which automatically sets up a humanoid avatar for VR and hand tracking. It comes with a built-in IK solver for the elbow joints, but also supports external tracking system data for body tracking. Also, it provides easy configuration possibilities for the finger and hand rotation joints. The avatar can then be used with different SDKs, such as the Meta XR Interaction SDK[8].

7.3 Discussion

We present a simple hand-scanning pipeline based on a camera rig that requires only very basic knowledge in 3D modeling, rigging, and avatar creation. While other approaches for 3D hand model generation can provide a higher visual quality, they are not necessarily usable with a usual VR-capable laptop or require more time and knowledge of avatar

[2] https://segment-anything.com/
[3] https://github.com/derekray311511/SAM-webui
[4] https://www.3dflow.net/3df-zephyr-photogrammetry-software/
[5] https://www.blender.org/
[6] https://extensions.blender.org/add-ons/mesh-repair-tools/
[7] https://www.mixamo.com/
[8] https://assetstore.unity.com/packages/tools/integration/meta-xr-interaction-sdk-essentials-264559

creation. Our approach can produce a fully functional, photorealistic hand model for VR within 30 minutes.

Another possibility for truthful hands in VR could be to make use of the video pass-through mode some HMDs provide and stream the detected hand image into the VE. However, this does not allow any control over the lighting condition of the hands, as they depend on the lighting in the real environment. Moreover, pass-through can be affected by lag or misalignment with the real hand position.

8

Conclusion

Part II of this thesis addressed the overall research question of how appearance and redirection contribute to the virtual hand illusion (**RQ1**), consisting of three questions that are concluded in the following.

RQ1.1: Does virtual hand realism influence Sense of Agency? To address this research question, we used the IB paradigm based on time estimation of an action (button press) and its outcome. We tested two levels of virtual hand appearance: a blue transparent hand and a more realistic hand, both fully articulated. While we could find SoA in both the IB paradigm and a questionnaire, there was no difference in the degree to which people felt SoA depending on the appearance of the virtual hand. We concluded that the difference between the two tested hand models was too small to find an effect on agency. In particular, we assume that SoA is more related to the anthropomorphism of the virtual hand than to its realism or truthfulness, as Ogawa et al. [193] also reported an effect of hand appearance on agency only between hand models with different degrees of freedom.

RQ1.2: Do motion direction and handedness influence redirection sensitivity? We then further investigated detection thresholds for virtual hand redirection to learn more about factors that might influence redirection sensitivity. We equipped users with size-adjusted whole-body avatars that could be used in social VR platforms or medical contexts. Using a staircase procedure, we determined detection thresholds for decelerated hand motions along 6 movement directions and found that redirection sensitivity significantly differs between both motion directions on each axis. For handedness, no effect on redirection sensitivity could be found.

RQ1.3: Does embodiment influence redirection sensitivity? We then combined both lines of research by investigating the effect of hand appearance on embodiment and redirection sensitivity. We used four different virtual hand models, varying in anthropomorphism and realism. While we could find an effect on embodiment, which was higher for the two more anthropomorphic hand models, we could not find an effect on redirection sensitivity. The effect on embodiment was particularly reflected in the *Ownership* subscale of the embodiment questionnaire, which is in line with previous works [8, 132, 133, 146, 157, 162, 193, 287]. Regarding detection thresholds, we could replicate our findings from [108], showing a difference in redirection sensitivity depending on motion direction for decelerated movements. Adding to this, for accelerated hand movements included in this work, a similar effect could not be found. This suggests that redirection sensitivity is a complex construct, depending on various factors, such as redirection method (gain-based or angular) [65, 112] or redirection mode (accelerated or decelerated)[108, 112].

In these works, we used virtual hand models of different appearances, varying both anthropomorphism and realism. However, truthfulness, the degree to which the virtual hand resembles the users' real hand, was not addressed. While we did not find an effect of hand appearance on SoA [106] or hand redirection sensitivity [112], we did find an effect on SoE, especially on ownership [112]. So possibly, embodiment could be even further increased using personalized, photorealistic hand models. We presented a pipeline that enables researchers to create such hand models fast and cost-efficiently, using a camera rig and open-source software for generating the hand model, and we show how such a model can easily be included in a Unity scene.

Part III

Beyond Hands: Interaction without (Virtual) Hands

9

Introduction to Interaction without (Virtual) Hands

In Part III of this thesis, we investigate concepts beyond the use of hands and their virtual counterparts, acknowledging the diversity of human bodies by investigating the role of self-representation for virtual whole-body avatars and exploring novel ways of interacting bimanually or without hand input at all. VR hardware and software often make assumptions about the user that reduce the diversity of human bodies. Often, when an application offers the possibility to create an own avatar, like in video games or social platforms, users can choose from predefined avatars or generate one on their own[1,2].

Regarding input techniques, XR systems usually offer hand-held motion controllers or hand tracking for interaction with the VE. Both of these technologies are typically designed for hands with five fingers and without motion impairments in mind [85]. Additionally, the applications often expect bimanual interaction, like operating a virtual gun or having specific tasks for both hands, and very few games offer a one-handed interaction mode [279]. A deviation from this assumption can make it hard or even impossible to participate in such virtual worlds, even if the condition is temporary, like a broken arm. More and more HMDs are equipped with eye-tracking technology, such as the Apple Vision Pro[3]. Here, gaze selection is the primary input method. The confirmation of the gaze selection is done with the hand by doing a pinch gesture.

Part III of this thesis is guided by ***RQ2****: How can VR systems be designed for the diverse human body in terms of virtual representation and input techniques?* RQ2 is divided into three research questions that are introduced in the following.

RQ2.1 What effect do truthfulness and self-representation have on embodiment? Due to the rise in popularity of VR and the metaverse, there has been a growing interest in the design of virtual avatars and how their visual appearance influences the user experience

[1]https://www.meta.com/avatars/
[2]https://community.secondlife.com/knowledgebase/english/controlling-your-avatars-appearance-r216/
[3]https://www.apple.com/apple-vision-pro/

(UX). Avatars enable the user to interact naturally within a VE, especially with full-body motion capture [264]. Earlier studies have shown various practical benefits of such a self-avatar that matches the human body in terms of morphology, leading to better distance and reachability estimations [59, 203, 212, 213] or the estimation of body weight [271]. Recent research also considered the influence of avatars on the therapeutic potential of VR applications [63, 270].

Previous studies have already investigated how changes in some dimension of avatar visual fidelity might support the SoE of a user towards an avatar, often focusing on the level of truthfulness [58, 94, 128, 221, 264], reporting a higher SoE for a higher level of truthfulness. Matching gender and ethnicity seem especially important for invoking an SoE and SoO [52]. At the same time, the results for realism remain inconclusive [128, 149, 221]. Döllinger et al. [58] compared SoE towards a generic, a customized, and a personalized photorealistic avatar and found increased SoE, but also increased eeriness, in the photorealistic condition. Also, photorealistic full-body scans can be time- and cost-intensive [1]. In addition, they tend to create uncanny [185] and eerie [58] sensations due to their nature of being imperfect visual reproductions [94, 149, 264] and were sometimes even inferior to manually modeled avatars [128].

However, self-avatars do not need to imitate the user's real look but can also be purposefully dissimilar to the user's real visual appearance. This offers the possibility to emphasize or hide aspects of the real body such as disabilities [288], gender [78], or age [18] and users might choose a dissimilar avatar to protect themselves from harassment and stereotype bias [18, 78, 288] or improve their self-confidence in social interactions [18, 78]. However, self-configured avatars can also be used to deceive others about one's own identity [18, 78]. While Part II of this thesis investigates the effect of hand realism and anthropomorphism on embodiment, in this part we focus on another dimension of avatar visual fidelity, truthfulness, which describes how close the visual appearance of the avatar is to the user. We interpret truthful in two ways: Firstly, based on the visual appearance of the user, and secondly, as the way the user wants to present themselves. In Chapter 10 we explore **RQ 2.1** by further investigating the role of user-configured avatars compared to photo-based and generic avatars in terms of user experience and embodiment. The results reveal higher ratings of attractiveness, valence, and threat reaction (as an indirect measure for embodiment) in the self-configured condition compared to the generic avatar. However, direct measures for embodiment remained inconclusive.

RQ2.2 What role does the secondary hand have in VR? VR has been critiqued as an *ableist* technology[4] [85], predominantly designed for *able-bodied* individuals. Many VR systems rely on dual-controller input or hand tracking with both hands, lacking essential accessibility features and alternative input methods for users with upper limb differences or limited fine motor skills [279]. Upper limb differences, whether congenital or acquired,

[4] https://www.ablegamers.org/thoughts-on-accessibility-and-vr/

encompass a wide spectrum of variations in the structure and function of the arms, hands, and fingers [13, 14, 152]. Over 5.6 million individuals in the United States alone are affected by limb loss or differences[5].

Assistive technologies such as EMG-controlled prosthetics [82, 159], motion tracking systems [45, 126], and gaze- or voice-based controls [204] have demonstrated promise in expanding access to digital interfaces. These modalities illustrate that it is possible to reimagine interaction beyond conventional bimanual input.

Gerling and Spiel [85] proposed three key hardware design strategies: (i) Embracing diverse body types, (ii) Challenging design norms, and (iii) Investing in individualized solutions. However, hardware barriers persist. Mott et al. [186] identified seven major accessibility obstacles, including the difficulty of manipulating dual motion controllers and inaccessible buttons for users with upper limb impairments. Naikar et al. [189] found that only 2 out of 39 free VR experiences offered a one-handed mode, while Yildirim [279] reported that only 5 out of 16 VR applications were fully usable with one hand. Beyond hardware, interaction techniques also pose challenges. Franz et al. [76] highlighted that users prioritize enjoyment, presence, and exercise over efficiency when selecting locomotion techniques, emphasizing the need for diverse options.

Despite progress in desktop accessibility, 3D immersive systems remain constrained by partly outdated paradigms. Existing guidelines like WCAG 2.1[6] offer useful principles for web and mobile content but lack transferability to VR contexts. Although initiatives such as XR Access[7] and Meta's VRCs[8] provide preliminary accessibility frameworks, they often focus on visual, auditory, or cognitive impairments—leaving physical impairments, such as upper limb loss, insufficiently addressed.

When designing features for people with disabilities, these innovations can also benefit a wider audience. This effect has also been referred to as the curb-cut effect [24, 151]. Curb cuts are small ramps that make sidewalks accessible for wheelchair users but are also appreciated by people with luggage, strollers, or those who have difficulties walking steps. The curb-cut effect belongs to the idea of universal design, which is a set of guidelines to create an environment that is usable for everyone, independent of their abilities. It consists of seven principles [247, 257]:

1. Equitable Use: Useful for people with diverse abilities.
2. Flexibility in Use: The design accommodates a wide range of individual preferences and abilities.
3. Simple and Intuitive Use: Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level.

[5] https://amputee-coalition.org/wp-content/uploads/Prevalence-of-Limb-Loss-and-Limb-Difference-in-the-United-States_Implications-for-Public-Policy.pdf
[6] https://www.w3.org/WAI/WCAG22/quickref/
[7] https://xraccess.org/
[8] https://developers.meta.com/horizon/blog/introducing-the-accessibility-vrcs/

4. Perceptible Information: The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities.

5. Tolerance for Error: The design minimizes hazards and the adverse consequences of accidental or unintended actions.

6. Low Physical Effort: The design can be used efficiently and comfortably and with a minimum of fatigue.

7. Size and Space for Approach and Use: Appropriate size and space is provided for approach, reach, manipulation, and use regardless of the user's body size, posture, or mobility.

A technology that meets several of these criteria is electromyography (EMG). EMG systems measure the electrical activity of muscles, which is produced when muscles are tensed. Signals are captured via electrodes that can either be inserted into the skin or attached to the skin. EMG is widely established in clinical and biomedical contexts, being used for diagnosing neurological and neuromuscular problems. Other applications range from gait analysis to physical therapy [209]. Additionally, EMG is a significant field of research in other applications, such as prosthesis control [12, 38, 43, 224]. It is a rising technology that is becoming more and more commercially available[9,10,11]. Such sensors can be attached to various muscles all over the body that are close to the surface and can be consciously controlled by the user. This property of EMG makes it usable according to one's own preferences or abilities (Guidelines 1 and 2). Moreover, the sensors and the whole system can be small, and the EMG system is capable of sensing a flexion of the corresponding muscle without the need to move the according body parts. This makes it not only space-saving but also offers the possibility to use EMG sensors as an input method without being observable to others (Guideline 7). So exploring novel input methods for VR is not only necessary to enable everyone to use it but can also pave the way to novel interaction paradigms and change the way we interact in and with VR systems.

In this work we present a user-centered design process to explore the role of the secondary hand in a bimanual interaction task. We developed three novel interaction techniques based on EMG and motion tracking with varying degrees of responsibility for the secondary hand: Selection, confirmation, or both. We evaluated them in two user studies: Firstly, we recruited 26 students to evaluate the efficiency and usability of the developed prototypes. Secondly, 4 participants with unilateral limb differences or motion restrictions provided feedback.

Results indicate that people with upper limb differences appreciated the proposed bimanual interaction techniques. We also found that those interaction methods can be as

[9] https://physio.kinvent.com/product-page/portable-emg-k-myo/
[10] https://www.biometricsltd.com/surface-emg-sensor.htm
[11] https://www.pluxbiosignals.com/products/electromyography-emg

efficient as unimanual interactions, even without prior learning, showing the potential of electromyography and motion tracking for bimanual interaction in VR.

RQ2.3 How does EMG-based input compare to traditional pinch gestures in terms of task efficiency, user experience, and cognitive load in user interactions? Using gaze as an input mechanism is becoming more and more popular in HMDs in the fields of VR and XR [12,13,14,15,16]. Eye tracking is a promising input technology [2, 124], as it does not require any hand motion to point in VR and, thus, can be more easily accessible and comfortable. While selection with eye gaze (referred to as gaze in the following) can be fast [251], selecting remains challenging due to the difficulty in distinguishing between observing an object and intending to select it. This phenomenon is commonly referred to as the Midas Touch problem [124]. Several techniques have been proposed for confirmation with eye tracking, such as using a dwell time in which the target needs to be fixated for some time until it is selected [102, 124], which often decreases the interaction efficiency. Furthermore, button pressing using a controller or hand gestures [124, 188, 202, 208], have been suggested. However, both approaches come with some accessibility barriers, as discussed above. The concept of gestures for gaze confirmation is not limited to the hand. While the hands can be well tracked using cameras that are built into the HMD, gestures of other body parts like the foot can be detected using EMG electrodes. However, which body gestures are comfortable and well usable remains an open question.

Chapter 12 explores EMG electrode placement on legs, arms, and the face and compares four methods for confirming gaze selection: (A) Palm lifting, (B) Finger tapping, (C) Biting, and (D) Foot tapping. In a preliminary study, we evaluated these techniques based on task completion time and user preference and compared them to a camera-based hand gesture selection method (pinching) as a baseline. Users performed specific gestures recognized via electrodes. Results indicated similar task completion times across all placements, with Foot tapping and Finger tapping preferred by users. We then conducted a user study assessing EMG-based confirmations with Foot tapping and Finger tapping versus a hand gesture method (pinching), using built-in hand tracking. Results show that while most participants preferred pinching, EMG-based gestures performed comparably and demonstrated potential as an alternative to camera-based confirmation techniques.

[12] https://www.apple.com/de/apple-vision-pro/
[13] https://www.magicleap.com/magic-leap-2
[14] https://forwork.meta.com/quest/quest-pro/
[15] https://www.vive.com/product/vive-focus-vision/overview/
[16] https://www.playstation.com/ps-vr2/

10 Influence of Avatar Appearance on the Sense of Embodiment and User Experience

Figure 10.1: Three avatars used by a participant during the study. From left to right: Generic representation with limited choices for gender and ethnicity. Self-configured avatar with instruction to strive for the best representation detached from physical appearance. Photo-generated avatar to match the physical appearance.

In this chapter, we present a study on the effect of different whole-body avatar appearances on embodiment, including a generic one, a self-configured version, and a photo-generated one. This chapter investigates **RQ2.1** and is based on the following pre-print:

J. Hartfill, F. Bormann, E. Wolf, and F. Steinicke. *The Influence of Avatar Visual Fidelity on Embodiment and User Experience in Virtual Reality*. 2025-07. DOI: 10.25592/uhhfdm.17711

10.1 Introduction

Consumer-grade VR allows embodying full-body avatars for interacting within virtual worlds. Realism and anthropomorphism have been shown to be an important factor for the plausibility and self-attribution of an avatar. However, the role of truthfulness and especially self-representation, which can diverge from the actual user's appearance, is not clear yet.

In this work, we compare a generic, a self-configured, and a photo-generated full-body avatar with similar realism levels in terms of embodiment and user experience. All avatars are created using the same tool, so they follow the same level of anthropomorphism and realism.

This chapter is structured as follows: Section 10.2 gives an overview of related research on avatar visual fidelity and diversity in avatar appearance. Section 10.3 describes the experimental setup and conduction of the study. Section 10.4 summarizes the results and their discussion, including the limitations and implications for future research (Section 10.5).

10.2 Related Work

10.2.1 Embodied Avatars as Virtual Identity

People's rationale for choosing the visual appearance of their virtual self-avatar can have several motivations [40]. In the context of immersive VR setups with HMDs and full-body tracking, reasons include aestheticism, showing an aspect of their identity, and adapting to or distinguishing from a social group [18, 78, 156]. Creating an avatar enables people to decide which aspects of their body to include in the avatar or not, such as gender [78] or disability [288]. While dissimilar avatars that hide aspects of the self can be chosen to avoid social exclusion or harassment [18, 78, 288], they can also be used to entirely change one's own identity to facilitate communication [18, 78] or to explore an ideal version of the self [156].

10.2.2 SoE Depending on Avatar Visual Fidelity

Maselli et al. found that realism is an important top-down factor for an ownership illusion that diminished the need for bottom-up factors like synchronous stimulation [175].

Waltemate et al. [264] investigated SoE with different levels of avatar personalization. They provided users with three different avatar representations as a within-factor: one generic hand-modeled, one non-personalized created with photogrammetry, and one created by a photogrammetry scan of the participant. In the HMD condition, participants were then immersed in a virtual room using those avatars from a first-person perspective in front of a virtual mirror with full-body motion tracking and received multiple movement instructions that incentivized them to pay attention to the visual appearance of their bodies. SoE and emotional response were assessed with several mid- and post-immersion questionnaires. In accordance with their initial hypothesis, they found ownership, presence, and dominance (according to SAM) to be significantly higher in the personalized scanned condition than in the other two. However, the two generic conditions did not differ in most measures. Hence, they attributed the effect to the factor of personalization (or truthfulness), as the scanned conditions did not differ in realism or anthropomorphism. Agency did not show any significant effect on personalization. Waltemate et al. did not encounter any uncanny valley effects, but they did not implement any measures for that [264].

This aligns with the findings of Salagean et al. [221] comparing different levels of personalization and photorealism in a 2×2 setup. The setup used in their experiments was similar to that of Waltemate et al. [264] with a full-body tracked first-person avatar in front of a mirror and multiple motion instructions. They found a higher SoO in the personalized (scanned) condition with high photorealism compared to all other ones and, in general, a positive effect of truthfulness and realism on the SoE. As an implicit measure of ownership, they induced a threat by a heavy box falling down near the avatar and measured the skin conductance response, but this did not reveal a significant effect.

Döllinger et al. [58] used three different truthfulness levels with a generic and a personalized photogrammetric avatar as extremes and a self-configured one with different, prepared body characteristics that allowed users to choose an avatar that matched their physical appearance from 67 representations in total. They explicitly found photogrammetric personalized avatars to invoke a greater feeling of eeriness, although the SoO was better.

Gorisse et al. [94] continued this research by implementing a setup with a third-person perspective. The conditions they realized used the same level of realism and anthropomorphism but differed in the degree of truthfulness. However, the first two versions used robotic representations without any similarities to the participant that either could or could not contain the human body due to their outer shape. Only the third version depicted a scanned version of the user's head. Similar to the previous results, they found the avatar version with the scanned representation of the user to induce a higher subjective SoO and abstract ones to allow for a stronger disconnection and risky behavior. However, some participants gave feedback hinting at a greater feeling of eeriness for the personalized avatar.

While most studies that investigate the effect of personalization focus solely on photogrammetric reconstructions, Jo et al. [128] added a cartoonish representation created by a 3D artist for each participant and found the SoO to be best compared to a generic and a highly realistic representation from a photo. However, they did not use tracking; instead, they used a Wizard-of-Oz setup that required participants to follow the avatar's movements.

Only very few previous works have examined the effects of customization without scanning or even with self-configuration in avatar depiction. However, they either focused on rather realistic renderings and constrained the choice to match the actual appearance [58] or did not implement a full-body tracking setup and lacked the comparison with a personalized condition on the same realism level [128]. The results of these studies remain inconclusive in terms of customization versus photorealistic personalization and miss any investigation of giving participants complete freedom over their avatars, only focusing on congruence with their real-world visual appearance.

10.2.3 Diversity in Avatar Appearance

As previously discussed, the visual appearance of an avatar and its similarity to the user impact the VR experience. Do et al. [52] aimed to investigate the importance of matching main features like gender or ethnicity. They provided users with four different avatars, each either matching or not matching their gender or ethnicity, that the participants embodied in front of a virtual mirror while performing multiple motion tasks. They found that matching ethnicity positively influences the SoE in general, and matching gender contributes to the SoO.

Do et al. [53] identified a lack of representation of different ethnic backgrounds in existing avatar libraries and identified the need for such a library focusing on diversity. To tackle this, they averaged publicly available photos as a basis for modeling 42 base avatars of different ethnic groups, each equipped with five different outfits, resulting in a total of 210 models. These avatars were then refined in an iterative interview process and validated via online surveys. The evaluation showed that most avatars were correctly attributed to the intended group. In their future work, they state that additional development is necessary to include more ethnic backgrounds, professions (by outfits), body types, age ranges, and gender, since only two genders are currently included in the library.

10.3 Experiment

10.3.1 Participants

Thirty people took part in the study. They were offered credit for their participation if applicable to their course of study. Seven identified as female, four as non-binary or genderqueer, and nineteen as male. Six of the participants were left-handed. The mean age was 24.93 ± 3.97 years. 22 had a computer science, six a psychology background. Ten people used glasses, and two used contact lenses for vision correction.

25 participants had used an HMD before. Except for four people who used it almost once a month and one who used it almost daily, all of them used it once every half a year or less. While 13 participants indicated experience with hand-tracking technologies before the study, only three mentioned any previous usage of full-body tracking.

10.3.2 Technical Setup

Experiments were conducted using the Meta Quest 2 and 3 HMDs with a resolution of 1832×1920 or 2064×2208, respectively, and a refresh rate of 120 Hz. The VR application was created using Unity and ran on a PC equipped with an Intel Core i9-10900K CPU with $10 \times 3.70\ GHz$, 32 GB RAM, and an NVIDIA GeForce RTX 3090 running Windows 10.

The participants' motions were tracked with the Sony *mocopi* system[1] that uses six sensors with accelerometers and gyroscopes placed at the head, wrists, hip, and ankles. The system estimates the position of the body parts using machine learning. This allows for an easy and cost-efficient motion-tracking solution. However, tracking errors will build up over time, and recalibration is needed to correct them. The sensor data was transferred via Bluetooth to an iPhone 15 Pro and sent to the PC via a Wi-Fi connection, since the system does not allow for a direct connection between sensors and the PC.

As the position and rotation of the character pose outputted by the mocopi system did not align with the head pose from the HMD that was used for calculating the perspective in VR, a position and rotation offset had to be calculated to avoid the user's view being placed outside the avatar's head. For doing so, the position of the avatar's head was fixed to the current head position calculated by the HMD. To compensate for rotational drift, the rotation offset around the vertical axis was constantly calibrated every five seconds as long as the viewing direction was within a 45 degree angle up or down from the horizontal axis, and the angular velocity did not exceed 5 degrees per second to avoid glitches by edge cases when looking up or down and during fast movements due to differing latencies. The avatar was manually resized according to the body height of participants specified during preparation.

The sliding feet problem (see Wolf et al. [269, 270]) would have been apparent here by a user looking down and moving their head, causing their whole body, including their feet, to move too, although their real feet remained in place on the ground. That could have happened as the body's position is fixed to the HMD's position and the latencies differ between the HMD and the other sensors. To compensate for that, a dual approach was used for the feet positioning: As long as the feet were not directly in the field of view of the user, the joint rotations of the legs and feet were directly taken from the *mocopi* system's output, as this provided the more natural-looking leg configuration and movement in the mirror. But if the feet became directly visible, they were fixed in place, and only the positional and rotational offset from that point on were used from the *mocopi* system, with the legs moved according to Unity's inverse kinematics.

The Meta Quest HMD tracked the positions of hands and fingers via inside-out cameras and image processing. The avatar's arms were placed according to Unity IK. In case the hands moved outside the tracked area or other tracking loss, the data from the *mocopi* system was used as a fallback (similar to Wolf et al. [270]) for the hand position smoothly

[1] https://www.sony.co.jp/en/Products/mocopi-dev/en/documents/Home/Aboutmocopi.html

morphing between the potentially differing positions in 0.5 s. The Meta Quest hand tracking data was also used to adapt the avatar's hand size to the participant automatically. To give the face a lifelike appearance, the HMD microphone captured the user's speech and transformed it into matching lip movements, facilitating the Oculus Lipsync plugin.

Within VR, users were placed in a simple room in front of a virtual mirror implemented with the Magic Mirror Pro Unity package. Instructions and questions were played back via audio and simultaneously displayed at the top of the mirror, similar to Salagean et al. [221].

10.3.3 Procedure

10.3.3.1 Preparation

After giving informed consent, the participants created their avatars to be used in VR, depending on the condition order. This order of conditions was counterbalanced.

In the generic condition *G*, they were offered 13 avatars that were created with the *Ready Player Me*[2] avatar creation tool from images of a selection of the VALID avatars [53] to offer various ethnicities and different genders and avoid a white male centered bias [52], while deliberately limiting their choice to very few options. Participants were instructed to choose an avatar that resembled their visual appearance the best, eliminating the necessity to make assumptions about the person's gender or ethnic background.

In self-configured *SC*, participants were allowed to create their avatar with *Ready Player Me*, giving them complete freedom over the look of their character. They were given the explicit instruction: "Please create the avatar in the way you would like to be represented in VR. This may coincide with your real-world visual appearance, but it does not have to." However, they were asked not to use any assets that impaired their vision or theoretical freedom of movement in any way.

In the photo-generated *PG*, a photograph was taken using an iPhone 15 Pro in front of a white background and uploaded to ReadyPlayerMe to create an avatar that, while having the same cartoonish style as the other ones, resembled the participant as closely as possible. After the automatic character creation process, participants were asked if they felt that the visual appearance of the avatar matched their own and offered the possibility to correct features that differed, especially if attributes like gender or hair color were incorrectly inferred from the image.

Following the character creation, the participants filled out a preliminary questionnaire. Then, the participants were equipped with the *mocopi* sensors and the VR HMD and were guided through the necessary calibration steps. If necessary, this calibration was repeated before each condition to limit the accumulated drift.

+aphics[width=0.8]figures/ingameview.png

Figure 10.2: Experiment from a participant's view during a movement task.

10.3.3.2 VR Exposure

Each condition followed the same structure, only differing in the avatar. Participants started in a virtual room with a mirror initially turned off. They were instructed to stand at a distance of about one meter from the mirror and give verbal answers to the mid-immersion questions, which were immediately transcribed by the experimenter.

After the experimenter started the task, the mirror was activated, and a set of movement instructions adapted from Waltemate et al. [264] was played back and simultaneously displayed at the top of the mirror (see Figure 10.2). Instruction 3 was adapted as the mocopi system had problems with the detection of high knees.

1. "Lift your right arm and wave to your mirror image in a relaxed way."
2. "Now wave with your other hand."
3. "Now walk in place."
4. "Now stretch out both arms to the front and perform circular movements."
5. "Now look right, stretch out your right arm to the side, and perform circular movements."
6. "Now look left, stretch out your left arm to the side, and perform circular movements."

During this, participants were repeatedly reminded to alternate between looking at the position of their virtual body and the mirror image following Waltemate et al. [264] to ensure that they perceived the visuo-motor synchrony between their movements and their virtual representation, supporting an ownership illusion [91]. In addition, it led to them actively looking at their virtual representation to maximize the time during which they could perceive differences between the conditions. An exception was made for the instructions where participants needed to stretch their arms to the side, as this would have caused their hands to be outside the sensory field of the Meta Quest inside-out cameras.

To assess an implicit measure of the SoO, after a randomly selected movement task, a virtual box was dropped left or right next to the participant to induce a potential threat reaction, similar to the procedure in Salagean et al. [221]. The subjective threat impression was captured by a mid-immersion question immediately following the stimulus (see 10.3.4.1).

When all motion tasks were finished, the participants were confronted with four questions to evaluate their impressions while still immersed in the VE with their avatar (see Section 10.3.4.1 for details).

[2] https://readyplayer.me/de

At the end of each VR exposure phase, participants were asked to place themselves at a distance from the mirror they felt the most comfortable with, which was then recorded by the experimenter with a button press. By that, the interpersonal distance chosen to the self-avatar in the mirror was recorded (see Section 10.3.4.4).

After each exposure, participants took off the HMD, filled out a post-immersion questionnaire, described in Section 10.3.4.2, and were offered a short break. At the end of the experiment, they filled in a general questionnaire regarding the experiment, could provide feedback, and ask further questions about the research purpose. The whole experiment, including the preparation phase, took one to two hours.

10.3.4 Measures

10.3.4.1 Mid-Immersion Ratings

While still immersed in the VE, participants were presented with five questions or statements in total. All statements had to be answered on a seven-point Likert scale from 1 to 7. The first one was asked immediately after the induced threat by the falling box to rate the statement, "I felt that my own body could be affected by the box." It served as an implicit measurement of the SoO like in [221] since a strong feeling of ownership has been shown to invoke a more intense reaction to a threat [10].

After the movement tasks were completed, all the other questions were asked to picture the feeling after a consistent time of self-observation and synchronous visuo-motor stimuli. Three of the questions were one-item measures for the components of SoE that also have been used in previous studies during the VR exposure [221, 264]: "To what extent do you have the feeling as if the virtual body is your body?", "To what extent do you have the feeling that the virtual body moves just like you want it to, as if it is obeying your will?", and "To what extent do you feel present in the VE right now?" The last question was complemented with an explanation of the concept of presence as the feeling of actually being there in the VE.

The final question addressed the attractiveness of the self-avatar to provide a mid-immersion counterpart to the corresponding post-immersion question (see Section 10.3.4.3 for details).

10.3.4.2 Virtual Embodiment Questionnaire

To assess the degree of the SoE and self-identification, the VEQ+ questionnaire [71] was used after each of the three conditions' VR phases. In this work, questions about self-location were excluded, as the virtual body always aligned with the physical body. The selected VEQ+ items used in this study are listed in Table 10.1.

10.3.4.3 Additional Questions

Three additional single questions complemented the previously described and validated questionnaires. The first one asked about the perceived attractiveness of the avatar: "To

Table 10.1: Selected items of the VEQ+ questionnaire [71] used in this work.

Dimension	Question
Ownership	It felt like the virtual body was my body.
	It felt like the virtual body parts were my body parts.
	The virtual body felt like a human body.
	It felt like the virtual body belonged to me.
Agency	The movements of the virtual body felt like they were my movements.
	I felt like I was controlling the movements of the virtual body.
	I felt like I was causing the movements of the virtual body.
	The movements of the virtual body were in sync with my own movements.
Change	I felt like the form or appearance of my own body had changed.
	I felt like the weight of my own body had changed.
	I felt like the size (height) of my own body had changed.
	I felt like the width of my own body had changed.
Self-Similarity	The appearance of the virtual human's face was similar to mine.
	The overall appearance of the virtual human was similar to me.
	I felt like the virtual human resembled me.
	The appearance of the virtual human reminded me of myself.
Self-Attribution	I felt like the virtual human was me.
	I could identify myself with the virtual human.
	I had the feeling the virtual human was behaving as I would behave.
	I felt like the virtual human had the same attributes as I have.

what extent did your avatar seem attractive to you?" This question captured satisfaction with the avatar's visual appearance. Previous research has shown a positive correlation between attractiveness and the level of truthfulness [94]. However, like many other measures used in this work, it has not been investigated in combination with freely self-configured avatars.

In addition, in this work we specifically investigate the participants' freedom of design and self-expression ("To what extent did you feel that you could express yourself in the virtual world?"). Also, all participants were given a chance to express free-form feedback after each condition concerning the specific avatar and general thoughts on their experience after finishing the last condition.

10.3.4.4 Mirror Distance

As already referred to in Section 10.3.3.2, while still immersed in the virtual setup, participants were asked to place themselves at a comfortable distance from the mirror, thereby determining a distance to the mirror image of their avatar. Previous studies have used this measure of interpersonal distance for social behavior in the company of virtual agents: They have found people to maintain a larger distance to agents compared to inanimate objects, but this distance decreased if the self-avatar was more attractive or the agent was presented with the participants face [15, 17, 277]. This may indicate interpersonal distance as an implicit measure of self-identification.

10.3.5 Design and Hypotheses

A within-subject design with a counterbalanced order of the three conditions with different avatar creation workflows was used, with either a limited choice between generic avatars, a completely customizable avatar, or an avatar generated based on a photo. The level of personalization or customization was the independent variable. As is apparent from the previous section, several dependent variables are recorded during the process: First, SoE was assessed explicitly both mid- and post-immersion in combination with self-identification as well as implicitly by the threat reaction and distance to the virtual self in the mirror. Due to the differing customization possibilities and different phrasing of the tasks in the condition, the following hypotheses are formulated:

H1 The photo-generated condition invokes the highest self-similarity.

H2 The customizable avatar shows a higher SoE.

H2.1 The higher SoE increases reaction to the threatening stimulus.

H2.2 The higher SoE decreases distance to the virtual self in the mirror.

The second hypothesis is based on the assumption that the participant's ability to customize their avatar freely to match their body image without necessarily showing their real-world appearance reduces the impact of the uncanny valley effect. By avoiding appearances that invoke an eerie sensation, they could choose more attractive features. As the UVI was also captured, this assumption is covered in **H3**.

H3 The uncanny valley reaction is lower in the customizable condition than in the photo-generated.

H4 The customizable avatar is perceived to be more attractive than the other avatars.

As the customizable condition gives more power over their preferred representation to the user, not being constrained by the number of options or their real-world appearance, it is also expected to create better ratings in the questions related to emotional reaction and user experience:

H5 The customizable avatar increases the emotional response, especially valence, compared to the other conditions.

H6 The freedom of choice results in a higher rating of the possibility to express oneself.

10.4 Results

The analysis of the results was conducted in R. The Shapiro-Wilk test was used to check for normal distribution. If the data was normally distributed, repeated measures ANOVA with optional sphericity correction was used to check for significant differences. In the non-normally distributed case, the Friedman test was performed. In cases with significant differences, a pairwise t-test or a paired Wilcoxon test was conducted, depending on the result of the preliminary test. An α of 0.05 was used for all statistical tests.

The questionnaires used to monitor the usability of the system revealed no issues interfering with the validity of the study: The System Usability Scale [130] resulted in a score of 74.2 which can be interpreted as good usability. The NASA TLX [103] score of 16.38 is inconspicuous. The VR Sickness Questionnaire [138] showed significant—according to the Wilcoxon signed-rank test with paired samples—but only little increases from the pre- to the post-questionnaire for eyestrain ($W = 0, p = 0.00601$, pre: $M = 0.1 SD = 0.305$, post: $M = 0.467 SD = 0.629$) and blurred vision ($W = 0, p = 0.0477$, pre: $M = 0.033 SD = 0.183$, post: $M = 0.233 SD = 0.504$).

10.4.1 Mid-Immersion Ratings

While still immersed in the VR setup, participants were asked several questions regarding their user experience and SoE, as stated in Section 10.3.4.1. A box plot of the results is given in Fig. 10.3. As the Shapiro-Wilk test showed a violation of the normal distribution, non-parametric tests were used to analyze the results.

A Friedman test revealed no significant effect of avatar fidelity on agency ($\chi^2 = 1.47, p = 0.481$), ownership ($\chi^2 = 2.70, p = 0.259$), and presence ($\chi^2 = 1.11, p = 0.573$). However, it showed a significant effect of this factor on the rating of attractiveness ($\chi^2 = 8.30, p = 0.0158$) and subjective threat by the falling box ($\chi^2 = 12.9, p = 0.00161$). A Friedman test conducted to investigate the factor of order revealed no significant effect of order for any of the questions.

For further investigation, the Wilcoxon signed-rank test with paired samples and Bonferroni correction was applied as a post-hoc test to the measures, with a significant effect. It revealed that participants rated the attractiveness of the avatar created by themselves (*SC*, $M = 4.47, SD = 1.61$) significantly higher than the generic avatar (*G*, $M = 3.83, SD = 1.62$) ($W = 38.5, p = 0.034$). The effect size was calculated as $r = 0.489$, which can be interpreted as a large effect according to Cohen [44]. In addition, it was found that the subjectively perceived threat by the falling box in *SC* ($M = 3.73, SD = 1.78$) was higher than in *G* ($M = 2.8, SD = 1.47$) ($W = 4, p = 0.000852$) with an effect size of $r = 0.646$ which can be interpreted as a large effect. All other post-hoc tests conducted on attractiveness and threat did not result in the finding of a significant effect.

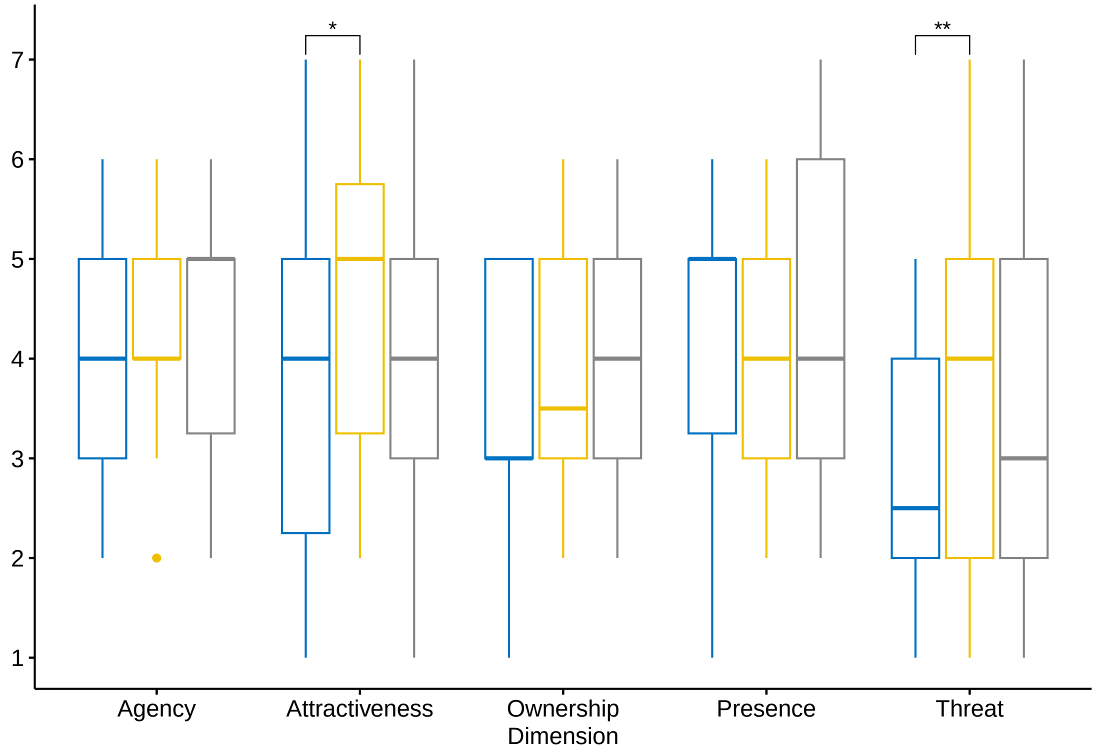


Figure 10.3: Mid-immersion ratings on agency, attractiveness, ownership, presence, and subjective threat by the falling box (Blue: G, Yellow: SC, Gray: PG, **: p < 0.01, *: p > 0.05).

10.4.2 Post-Immersion Ratings

After each of the three VR exposures, participants were asked to complete several surveys to get a detailed view of their emotional response, user experience, and SoE.

10.4.2.1 Virtual Embodiment Questionnaire

To record the SoE and the experience of self-similarity as well as self-attribution, the participants had to answer a questionnaire adapted from the VEQ+ [71] as it is described in Section 10.3.4.2. Answers were aggregated by mean for each participant and the five dimensions: agency, body ownership, change, self-attribution, and self-similarity (see Figure 10.4). The Shapiro-Wilk test showed a violation of the normal distribution for questions regarding change and self-similarity in some conditions. The results of these categories were analyzed using the non-parametric Friedman test.

As all other answers followed a normal distribution, repeated measures ANOVA was used. It revealed a significant main effect of avatar visual appearance for self-attribution ($F(1.93, 55.9) = 4.83, p = 0.013$). With an $\eta^2 = 0.093$, the effect size can be interpreted as medium. No significant main effect of avatar visual fidelity was found for the other dimensions, i.e., agency ($F(1.9, 55.2) = 0.473, p = 0.616$) and body ownership ($F(1.94, 56.2) = 2.50, p = 0.093$). A pairwise comparison with a paired t-test with Bonferroni adjustment was conducted as a post-hoc test to investigate the particular differences

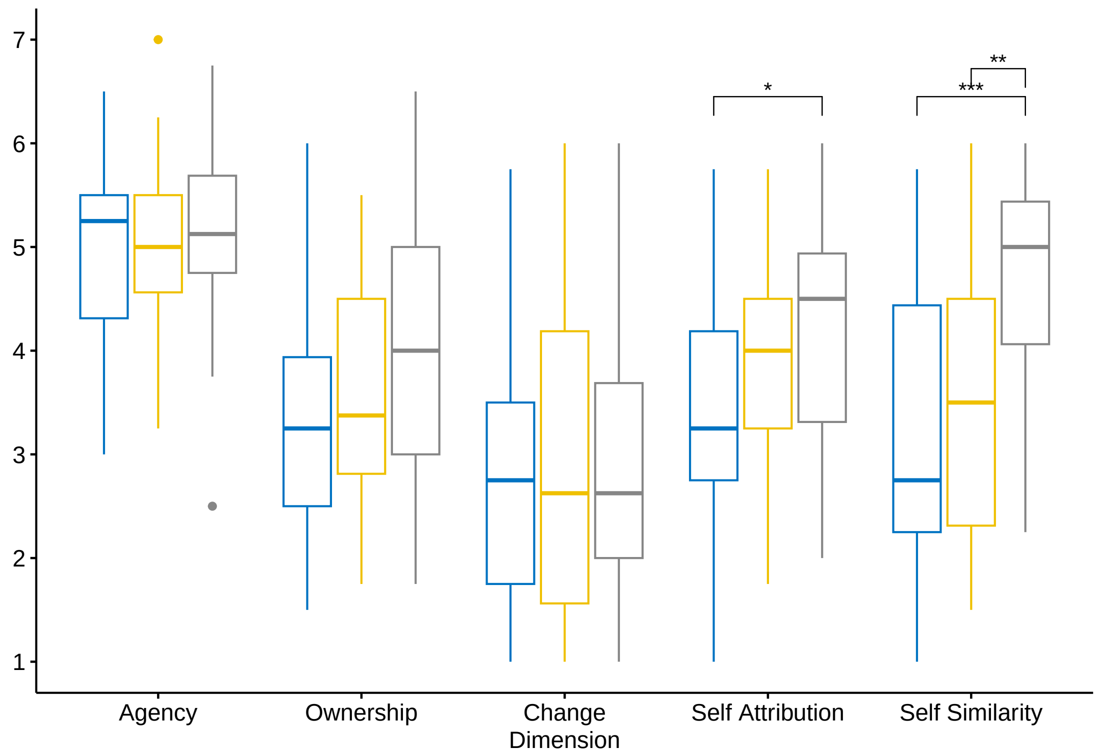


Figure 10.4: Results of the VEQ+ (Blue: G, Yellow: SC, Gray: PG, ***: p < 0.001, **: p < 0.01, * p > 0.05).

between the conditions. It showed the generic avatar (G, $M = 3.42, SD = 1.51$) to have a significantly lower score in self-attribution than the avatar generated by photo (PG, $M = 4.21, SD = 1.50$) ($t(29) = -2.83, p = 0.025$). A calculation of Cohen's d resulted in $d = -0.517$, which indicates a moderate effect size.

The non-parametric Friedman test was used to analyze self-similarity and change, which showed a significant main effect of avatar visual fidelity for self-similarity ($\chi^2 = 13.6, p = 0.00110$). A signed-rank Wilcoxon test with paired samples and Bonferroni adjustment was conducted to further explore which differences between the samples contributed to this effect. This indicated that self-similarity ratings were significantly higher using the photo-generated avatar (PG, $M = 4.68, SD = 1.24$) compared to the generic avatar (G, $M = 3.18, SD = 1.37$, $W = 31, p = 0.000166$) and the self-configured avatar (SC, $M = 3.52, SD = 1.51$, $W = 69, p = 0.007$). The effect size was calculated to be $r = 0.741$ comparing PG to A and $r = 0.570$ comparing PG to B, both of which can be interpreted as large effects.

In all other dimensions, no significant effect of avatar visual fidelity was found. While ANOVA revealed no statistically significant effect for body ownership ($F(1.94, 56.2) = 2.50, p = 0.093$), a visual inspection of the results using a box plot (see Figure 10.4) suggested a possible trend in body ownership, which is supported by a Cohen's d of $d = 0.301$ for the comparison of PG and A, indicating a small effect size. However, as stated before, it is not strong enough to be considered statistically meaningful, which is

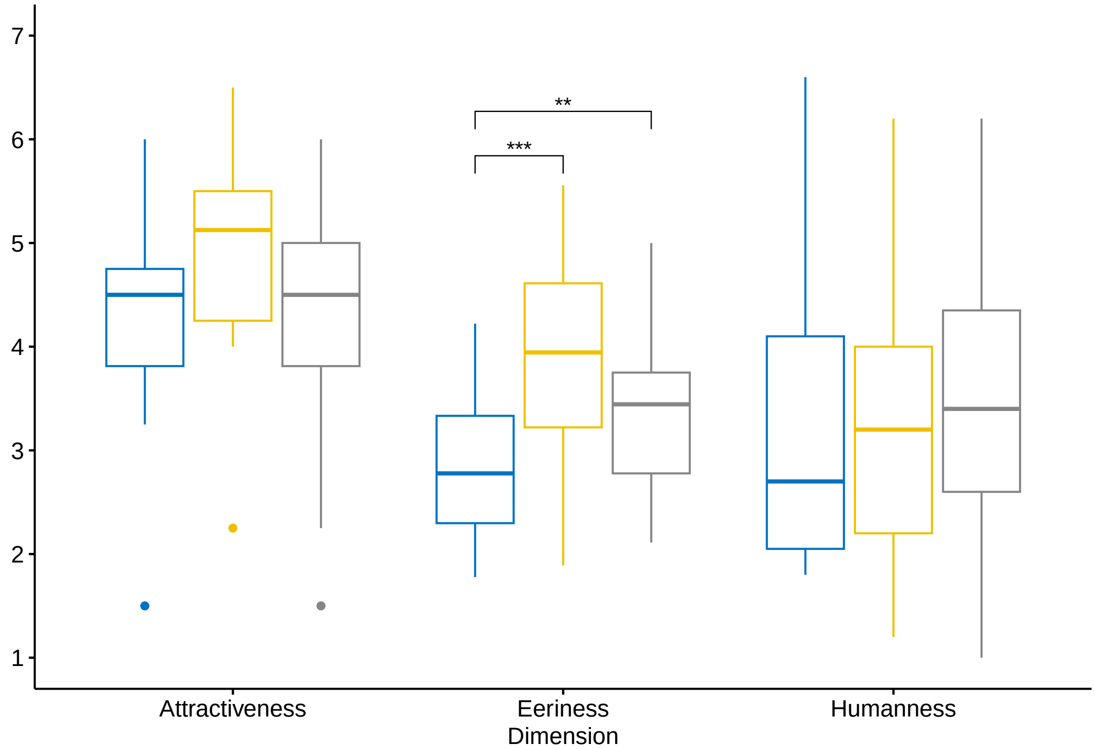


Figure 10.5: Results of the UVI (Blue: G, Yellow: SC, Gray: PG, ***: p < 0.001, **: p < 0.01).

also confirmed by a t-test with Bonferroni adjustment ($t(29) = -1.65, p = 0.33$).

As a visualization of the data (see Figure 10.4) might suggest a difference in variance for change and self-similarity, this was checked with Levene's test, revealing no difference in variances in any category.

The preceding tests were repeated with order as the considered factor to check for potential effects of condition order. In some cases, the Shapiro-Wilk test showed a violation of the normality assumption in agency and change. Those dimensions were analyzed using the non-parametric Friedman test. For the other ones, repeated measures ANOVA was used. The ANOVA showed no statistically meaningful effect of order for body ownership ($F(2, 58) = 0.0647, p = 0.9374$), self-similarity ($F(2, 58) = 0.4705, p = 0.627$), or self-attribution ($F(2, 58) = 0.7714, p = 0.4671$). Similarly, no significant main effect of order was found with the Friedman test for agency ($\chi^2 = 2.25, p = 0.325$) and change ($\chi^2 = 4.93, p = 0.0849$).

10.4.2.2 UVI Questionnaire

To assess the impact of the uncanny valley effect, participants filled out the Uncanny Valley Index questionnaire [117]. The results were aggregated by mean for each question dimension: Attractiveness, eeriness, and humanness (see Figure 10.5). A preliminary Shapiro-Wilk test showed a violation of the normal distribution assumption in all three dimensions, so nonparametric tests were used for analysis.

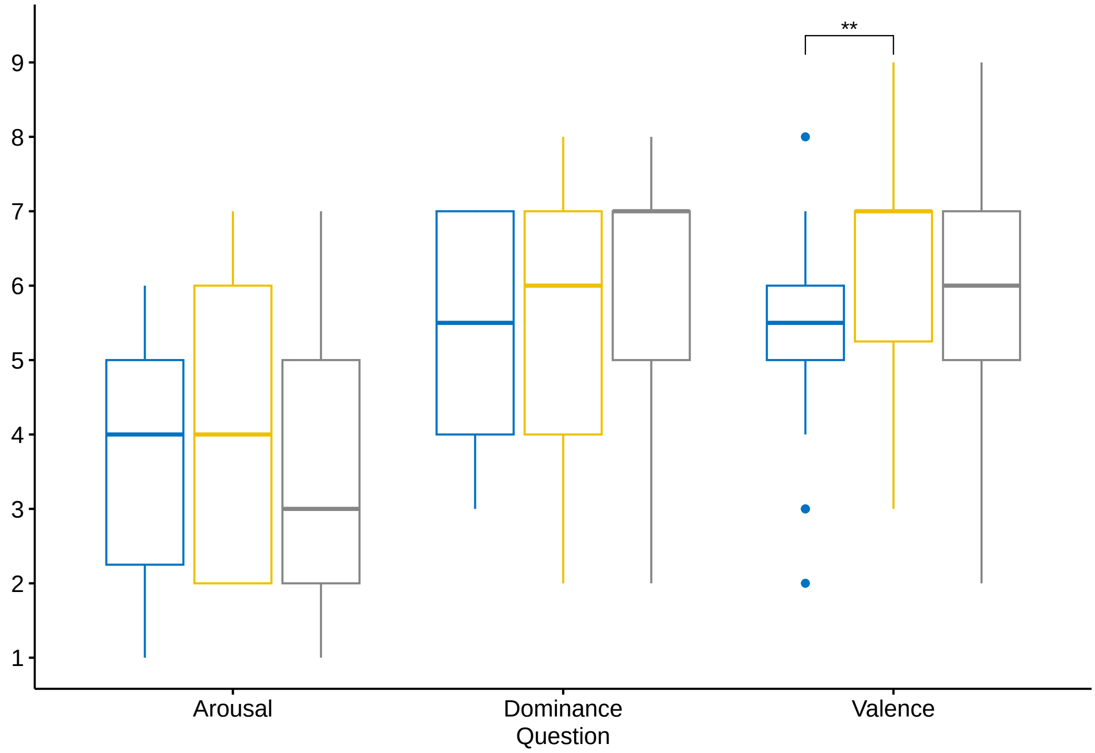


Figure 10.6: Results of the Self-Assessment Manikin questionnaire (Blue: G, Yellow: SC, Gray: PG, **: p < 0.01).

A Friedman test showed a significant main effect of avatar visual fidelity for eeriness ($\chi^2 = 13.8, p = 0.00101$) and humanness ($\chi^2 = 6.39, p = 0.0410$) while attractiveness revealed no clear effect ($\chi^2 = 4.88, p = 0.0870$). To further investigate these effects, the signed-rank Wilcoxon test with Bonferroni correction was used as a post-hoc test to check for significant pairwise differences. Considering the dimension of eeriness, it was found that the ratings were significantly higher for the self-configured avatar (SC, $M = 3.79, SD = 1.06$, $W = 32.5, p = 0.000324$) and the photo-generated avatar (PG, $M = 3.28, SD = 0.74$, $W = 78, p = 0.008$) compared to the generic avatar (G, $M = 2.84, SD = 0.688$). The effect size was calculated as $r = 0.701$ for comparing G and SC and $r = 0.552$ for comparing G and PG, both of which can be interpreted as a large effect. However, the pairwise comparisons of the conditions regarding the humanness ratings did not reach statistical significance, which might indicate that the sample size was too small to detect a specific difference between any two conditions. A visual inspection of the attractiveness results might suggest further differences that are supported by a calculation of the effect size ($r = 0.463$ for G and SC, $r = 0.334$ for SC and PG). Nevertheless, it has to be stated that as the differences did not reach the significance level ($\alpha = 0.05$), they cannot be considered statistically meaningful, and further research is necessary to check this.

10.4.2.3 Self-Assessment Manikin

To investigate the emotional response to the VR exposure depending on the avatar visual fidelity, participants completed the Self-Assessment Manikin questionnaire [30] by selecting on a scale from 1 to 9 which picture most resembles their emotional reaction to the preceding experience (for a visualization of the results, see Figure 10.6). The Shapiro-Wilk test showed several violations of the normality assumptions through all questions and conditions, so non-parametric tests were used to check for statistical significance.

A Friedman test indicated a significant main effect for valence ($\chi^2 = 6.44, p = 0.0400$) while arousal ($\chi^2 = 3.27, p = 0.195$) and dominance ($\chi^2 = 4.63, p = 0.0990$) did not reach significance. As post-hoc tests, a pairwise comparison with the signed-rank Wilcoxon test revealed that the self-configured avatar (SC, $M = 6.33, SD = 1.40$) was significantly higher than the generic avatar (G, $M = 5.33, SD = 1.35, W = 36, p = 0.005$) with an effect size of $r = 0.536$ which suggests a large effect according to Cohen [44]. All other comparisons did not show a statistically meaningful effect.

As the visually different distributions (see Figure 10.6) might suggest a difference of variances, especially for valence, Levene's test was conducted, revealing no significant differences.

10.4.2.4 Additional Questions

In addition to the established questionnaires, some questions were added as stated in Section 10.3.4.3. The first added question asked to what degree participants felt they could express themselves in the VE. As the Shapiro-Wilk test indicated a violation of the normal distribution, the non-parametric Friedman test was used to check for a significant main effect of the condition, but no such effect was found ($\chi^2 = 2.34, p = 0.310$).

To complement the mid-immersion question asking explicitly for the attractiveness of the avatar, the same question was added to the post-immersion questionnaire since all other questions asked during the VR exposure were taken from established questionnaires already part of the post-exposure surveys (see Section 10.3.4.3). A box plot of the result is given in Fig. 10.7. Because of a violation of the normal distribution shown by the Shapiro-Wilk test in some conditions, the Friedman test was used to analyze the results. It revealed a significant main effect of condition ($\chi^2 = 9.38, p = 0.00917$).

For further investigation of this effect, the signed-rank Wilcoxon test with Bonferroni correction was applied to check for pairwise differences: The attractiveness ratings for the self-configured avatar (SC, $M = 4.57, SD = 1.70$) appeared to be significantly higher than the generic (G, $M = 3.67, SD = 1.49, W = 48, p = 0.009, r = 0.549$) and the photo-generated avatar (PG, $M = 3.93, SD = 1.60, W = 168, p = 0.047, r = 0.399$). The effect size can be interpreted as large and moderate, respectively.

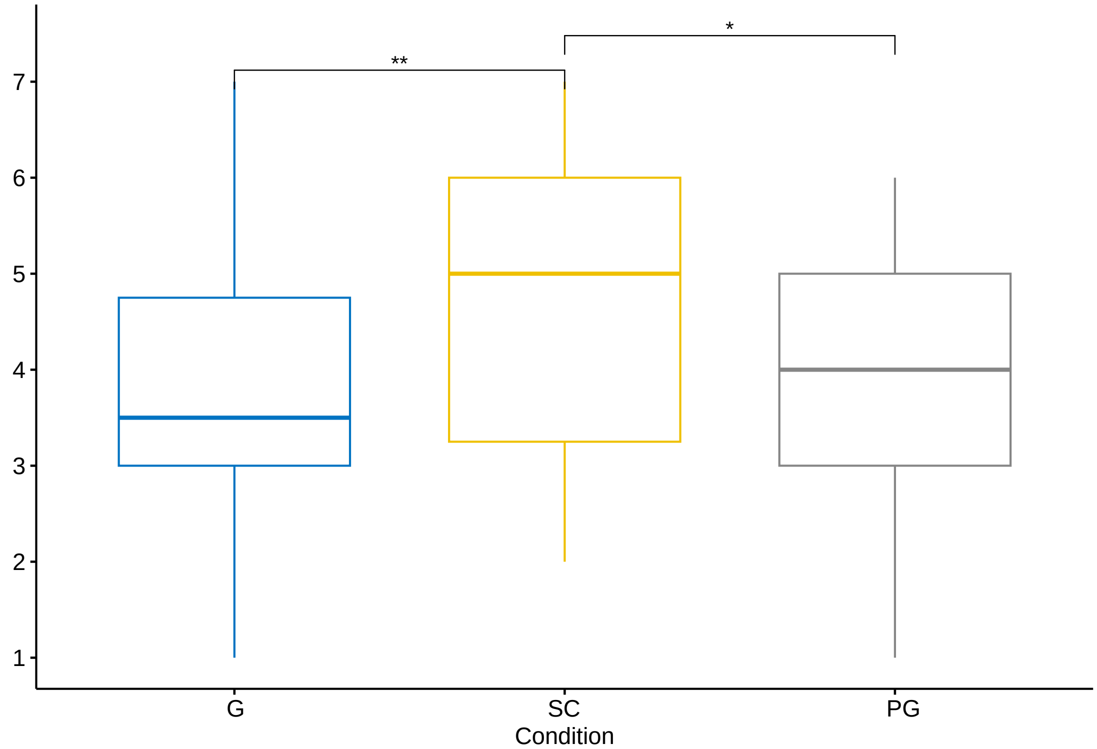


Figure 10.7: Results of the post-immersion attractiveness rating (**: p < 0.01, * p > 0.05).

10.4.3 Mirror Distance

At the end of the exposure, participants performed a positioning task in front of the mirror described in Section 10.3.4.4 as a potential implicit measurement of attitude to the avatar. The z-axis values of the recorded coordinates were evaluated for a significant effect of condition. As the preliminary Shapiro-Wilk test did not show a violation of the normal distribution assumption, repeated measures ANOVA was used. This indicated no significant main effect of avatar visual fidelity on the distance participants took to the mirror ($F(1.65, 47.92) = 0.73, p = 0.462$).

10.4.4 Qualitative Data

After each VR exposure phase and at the end of the experiment, participants were provided the opportunity to give free-form feedback. Concerning general problems, several participants criticized the lower body's tracking as imprecise, having latency, or leading to sliding or hovering feet. Some also noted problems with the layout and positioning of the arms, especially when right next to the body, as the hands sometimes clipped into the body or at least the outer clothing due to imprecise tracking ("My hands [stuck] in my avatar, so there were times when I got the feeling of losing control/the avatar not being me, although sometimes it felt like it was me."). Some tried intuitively to overcome the imperfections by taking poses that matched the avatar they viewed in the mirror. When the arms were stretched forward, some body types and clothing led to impressions of unnatural body configurations ("[like] an inflated rubber suit"). Despite the automatic resizing of the avatar's hands, some participants mentioned their hands being bigger than their real hands. However, most of the participants emphasized the good tracking of their hands and fingers, even being surprised by it ("[When] looking through [the] space between HMD and nose, the virtual arm and physical arm seemed to match pretty well").

Concerning the avatar, many participants criticized the limited choice of only two genders, stereotypical body types, everyday clothing, and missing diversity in facial appearance. People who did not identify as cisgender missed the opportunity to either not specify a (binary) gender at all ("[One] should be able to create an avatar without having to specify gender and just straight up choose a body type") or at least configure the body type more detailed to fit the desired appearance ("[The] character creator also only allows 4 different body types to be chosen per gender and even though I am feminine, my body does not reflect this, so I was unable to even create an avatar that matches my real body in certain aspects because the editor did not allow me to choose [. . .] another body shape than an hourglass figure", "[Those] avatars are quite gendered, especially the female ones").

The avatar-specific feedback did not reveal clear preferences beyond personal likes. However, it did show some valuable insight into potential reasons for the quantitative results. If specifically referenced, the generic avatar was mainly described as not looking like oneself—disturbing identification with it—or even bland or boring and less fun. In contrast, one participant also mentioned the lack of similarity as a potential advantage: "It's so generic that you notice less the differences between you and the avatar and can project more onto it."

The feedback on the other two avatars was also mixed. While the customizable one was most often associated with fun and the pleasure of being able to create it according to one's wishes, some people felt the visual differences in the appearances from their own body that they deliberately chose prevented a stronger self-identification: "I think I could identify less with my own created character because he has a very different appearance than me." "I was surprised to find myself not liking the character I made to look "cool" or finding her more difficult to navigate, although I was looking forward to her." Still, there were participants who explicitly preferred it over the two other options.

In the photo-generated condition, some participants mentioned that they liked it the most as it represented them the most or even referred to a depressing feeling with the other avatars coming from a visual mismatch between the avatar and themselves in the other conditions. Interestingly, it was also the only condition leading to people stating a repelling feeling toward their virtual face or being bothered by the close but imperfect reproduction of their appearance: "The character that was supposed to look like me was weird to look at because you wanted to eradicate the differences."

10.5 Discussion

First, the higher self-similarity found for the photo-generated avatar compared to the two other variants proves hypothesis **H1** and validates the desired distinction between the conditions, i.e., participants did not just create avatars that resembled themselves and, therefore, did not differ enough to draw meaningful conclusions from the other questionnaires. The same applies to the dimension of self-attribution. However, there is no significant difference to the self-configured avatar, which might be related to users configuring avatars that differed from their visual appearance without interfering too much with self-attribution. However, it does not support the assumption that users given complete freedom over the visuals of the avatar create a character that might even improve their self-attribution. Reports of that, e.g., creating a "cool" character that they could not identify with, were also found in the qualitative feedback about the self-configured avatar. This raises the question of the importance of the prompt given to the user for creating the avatar and the surrounding procedure. Future research should further evaluate different versions of it to explore their effect on self-attribution.

Considering the core dimensions of the SoE, neither mid- nor post-immersion questionnaires showed a clear difference. In particular, agency received high ratings post-immersion throughout all conditions, with a low spread. Despite the criticism of the technical difficulties (see Section 10.4.4), this implies that the setup was, in general, suitable for creating the desired illusion. The missing difference in the scores between the conditions is in line with previous findings manipulating the truthfulness of avatars [58, 221, 264] explained by agency mainly being related to the coherence of visuo-motor cues that were not manipulated here. The missing differences for presence [221] and change [58] also align with former findings, as change is more important in setups that deliberately manipulate the avatar to differ from the user, which is not the case here.

While visual inspection also does not hint at a difference between the conditions for those dimensions, it suggests a trend for the SoO in the post-immersion VEQ questionnaire, even if it is not statistically significant. The small effect size indicated by Cohen's d can be interpreted so that a potential effect was too small to be detected with the present sample size. This assumption is well-founded on previous studies [58, 221, 264] showing a greater SoO related to higher truthfulness that would at least explain a greater body ownership for the personalized avatar compared to the generic one. However, the statistical insignificance of the results prevents us from making a clear statement on hypothesis **H2**.

In terms of indirect measures, the reaction to the induced threat showed a greater reaction for the self-configured avatar compared to the generic, which was not achieved by the photo-generated, providing partial support for **H2.1** and implicitly hinting at higher ownership for the self-configured avatar [10, 221]. Due to the lack of differences in the explicit ownership ratings, the final interpretation is unclear, though. The absence of a significant main effect on the distance taken to the mirror might be explained by missing motivation to move as close as acceptable by social standards. In previous experiments, this has been done by memorization tasks for visual features [15] or explicitly asking participants to move closer [277] so a refinement of the task is necessary to investigate the hypothesis **H2.2**.

Aligning with earlier studies [94, 149], the UVI showed a higher eeriness rating for the photo-generated avatar than the generic. A reason might be due to the generic being easier to dissociate from (see Section 10.4.4). However, since the same is true for the self-configured avatar compared to the generic, and there is no meaningful difference between the self-configured and the photo-generated condition, it could be interpreted as a general effect from a stronger emotional reaction to a non-generic avatar, and the results do not support **H3**.

Although higher eeriness ratings and the expectation of a better SoE may seem contradictory, earlier experiments have observed exactly these counterintuitive behaviors [58, 94]. In their conclusion, Döllinger et al. [58] also called for further investigation of the "complex interplay between personalization, VBO, [and] eeriness." Our results leave this to be at least partially inconclusive and therefore support the necessity for further research, especially since no statistically significant difference was found between the self-configured and the photo-generated condition.

In other regards, participants seemed to be satisfied with their self-configured avatar, showing higher valence ratings and partially confirming **H5** for the comparison with the generic avatar, which might be interpreted as them enjoying the ability to customize according to their wishes. The absence of differences in the other dimensions of the Self-Assessment Manikin probably results from very few other stimuli creating an emotional reaction. At the same time, valence could be invoked by just the pleasure of using a preferred avatar. The effect of the personalized avatar is unclear, though.

The satisfaction with the self-configured avatar also shows in the high attractiveness score in mid- and post-immersion questions, confirming **H4**, which thereby dampens the negative effects that one otherwise might deduce from the eeriness ratings. As previously mentioned, earlier studies have shown a positive correlation between attractiveness and truthfulness. However, these results show that giving people the power to decide on their own appearance can even improve this.

Finally, the lack of a main effect on the question targeted at the possibility of expressing oneself might be due to the question's phrasing being too generic to capture a specific effect, such that it may be insufficient to make a statement on **H6**.

10.6 Limitations and Future Work

As mentioned in previous sections, this work faces some limitations in tracking and avatar creation that should be considered and improved in future research. However, they do not significantly undermine the conclusions drawn from the results.

First, a lack of tracking fidelity or imprecisions that some participants noticed in the lower body and arms when they left the area that was captured by the visual tracking is generally considered harmful to the SoE [67] and especially the SoA [136]. However, the

SoA was still rated high in all conditions, implicating the capability of the users to adapt to this situation, maintaining a strong illusion described by Won et al. as some kind of homuncular flexibility [272]. In addition, these shortcomings were consistent throughout the experiment and, therefore, did not impact the comparison between the avatars.

Second, the visual style of the avatars has been criticized by participants for representing stereotypic body images with vastly differing body shapes depending on the choice of gender in the editor. While the study was deliberately designed to use a cartoonish avatar appearance, this limits the freedom of users to configure an avatar to their liking or their actual physical appearance. The importance of this becomes even more apparent if you consider non-cisgender participants who have been constrained to choose a binary gender for all of their avatars, which might be incongruous with their identity and even more problematic with very gendered shapes of the avatars. While current research emphasizes the importance of gender-matched avatars [52], avatar libraries are often missing non-binary representations, and to the knowledge of the author, there is currently no research considering how the best avatar representations can be achieved for trans* and non-binary people who could largely benefit from a self-determined visual representation in VR. After much progress has been made in the ethnic diversity of avatars recently, much more research is needed on gender diversity.

As the hypotheses of this study largely assumed the potential of higher satisfaction with a self-configured avatar that does not necessarily look like the actual physical appearance of the user, there have been several questions regarding the SoE, emotional response, and attractiveness that could capture the satisfaction with the avatar. However, the questionnaires lack measures to capture self-esteem and satisfaction of the participants with the actual look of their body that could justify interpersonal differences in the potential of a self-configured avatar, as those factors were not considered in time. Gorisse et al. [94], e.g., have found that people with lower self-esteem prefer more abstract representations. In comparison, when asked, people with higher self-esteem chose representations more similar to them. Future studies should include adequate measures for that, like the Rosenberg self-esteem scale [216], and explore other potential factors for interpersonal differences.

Finally, there was no compensation for the time participants spent longer with the self-configured avatar due to the necessary configuration time. However, it is only to be expected that this contributed to a change in the SoE to a limited extent, as the decisive elements for a corresponding illusion, such as perspective or synchronous visuo-motor stimuli, were missing.

10.7 Conclusion

In this work, we used the consumer hardware mocopi tracking system to compare three avatar representations with a varying degree of truthfulness. The motion tracking setup was cost-efficient and generally suitable for this application. While it produced noticeably imprecise tracking results, especially in the lower body area, the general illusion, as well as the additional sensor input and heuristics used as countermeasures, appeared to be effective, resulting in a good SoA.

While the intended differences in truthfulness of the generic (gender- and ethnicity-matched), the self-configured, and the personalized photo-generated avatar were proven by questions for self-similarity, the explicit questionnaires for the SoE remained largely inconclusive and provided only insignificant trends hinting at a positive contribution of truthfulness to ownership that would be in line with previous research.

The expected positive effect of a self-configured avatar because of the potential of representation without the limit of physical appearance and intuitive avoidance of uncanny features could not be clearly shown, as both the self-configured and the photo-generated avatar created a more eerie sensation than the generic one. However, the indirect measure of threat reaction and the emotional reaction showed the advantages of the customizable representation. Those benefits and the creation pipeline requiring significantly less hardware than photogrammetric setups used in other studies definitely motivate further investigation of the potential of self-configured avatars for VR applications.

To investigate individual differences, future research should include questionnaires assessing the self-esteem of participants, since this could explain differences in the preference for visual similarity to the physical self [94]. In addition, the study revealed a large gap in the diversity of gender representation in common avatar libraries that should be considered in future development.

While this work focused on the effect of different visual appearances of whole-body avatars, the question remains, how can such avatars be controlled beyond conventional input methods such as motion controllers and hand tracking? While many real-world tasks are bimanual, in the following chapter we investigate the role of the secondary hand in VR. We present a user-centered design process in which we developed three interaction techniques for bimanual tasks in VR with varying levels of responsibility and compare them to a conventional unimanual mode.

11

User-Centered Design of Bimanual Interaction Techniques

Figure 11.1: A participant with unilateral upper limb differences illustrating the different tested interaction techniques based on EMG and motion tracking. From left to right: Interaction with only one motion controller, Secondary hand is responsible for confirming, Secondary hand is responsible for selecting, and Secondary hand has confirming and selecting responsibility.

This chapter investigates how to make bimanual input more accessible and inclusive using electromyography and motion tracking. Through an inclusive user-centered design approach, we developed three interaction techniques after interviewing a person with unilateral upper limb differences. To assess baseline metrics on the efficiency and usability of the three prototypes, a user study was conducted with 26 participants without upper limb differences. In a second user study, feedback was gathered from four participants with unilateral upper limb impairments to refine the interaction techniques and identify accessibility barriers in the design. This chapter investigates **RQ2.2** and is based on the following publication:

> J. Hartfill, S. Hajahmadi, S. Schmidt, G. Marfia, and F. Steinicke. "Embracing differences in virtual reality: inclusive user-centered design of bimanual interaction techniques". In: *Frontiers in Virtual Reality* Volume 6 (2025). ISSN: 2673-4192. DOI: 10.3389/frvir.2025.1586875

11.1 Introduction

Many real-world tasks are inherently bimanual, requiring coordinated hand use where each hand assumes a distinct role—typically, a primary hand for action and a secondary hand for support or stabilization [116, 220].

Even in activities often perceived as one-handed, such as writing, the non-dominant hand plays a crucial role by steadying the paper while the dominant hand writes. Technical tasks further highlight the necessity of bimanual coordination: assembling mechanical components usually involves holding parts in place with one hand while manipulating a tool like a screwdriver or soldering iron with the other. In laboratory settings, technicians frequently use one hand to operate delicate instruments while simultaneously recording data or adjusting parameters with the other. Surgeons, too, depend on precise bimanual coordination to manipulate instruments, using one hand for action and the other for retraction or stabilization.

This principle extends to interactions with visual display systems. For example, people often hold a smartphone in one hand while tapping, scrolling, or typing with the other. Similarly, laptop users may use one hand to navigate with the trackpad or mouse while the other executes keyboard commands. These everyday scenarios underscore how deeply bimanual coordination is embedded in our interactions with technical systems and digital interfaces. Given the ubiquity and importance of bimanual coordination in everyday contexts, it is no surprise that interactive technologies—particularly immersive systems such as VR—increasingly replicate and rely on two-handed input paradigms to support naturalistic interaction.

In VR environments, bimanual interactions are commonly replicated to enhance realism and immersion, aligning with users' preferences for bimanual engagement [255]. Our study addresses this gap by exploring the potential of electromyography (EMG) and motion capture technology as input methods, enabling users with diverse motor abilities to engage with VR. These technologies can replicate fundamental functionalities of the conventional controller or hand-tracking interaction in VR: selecting, usually done by moving the controller or the hand directly, can be realized with any motion capture system. Confirming, typically done using a button on the controller or a gesture for hand tracking, can be realized by using a simple threshold function on the EMG data. This means that the user needs to flex the appropriate muscle shortly for the selection to be confirmed. By introducing these alternative interaction techniques, we demonstrate how accessibility in VR can be improved at both the software and hardware levels, reducing reliance on standardized input methods and expanding usability for a broader range of users. However, it is important to clarify the intended user group. The interaction techniques developed in this study are primarily suited for individuals with partial upper limb functionality—particularly those with unilateral limb differences who retain residual muscle control, such as in the biceps—which can be leveraged for EMG input or upper limb motion tracking [82]. For users with complete limb absence, especially without viable musculature, the current methods may not offer immediate applicability. Nonetheless, the inclusive design principles and input flexibility explored here offer a foundation for extending accessibility to a broader population. Future adaptations could integrate other modalities such as foot-based EMG, voice commands, or gaze-based interaction to accommodate more severe impairments [204, 234, 282].

We developed three interaction techniques for VR interaction techniques in an inclusive, user-centered design approach. We conducted an interview with a participant with unilateral limb differences to gain insights into his experience with conventional PC gaming—using mouse and keyboard—and what could be transferred to VR input systems. One of the core results of the interview was that the participant uses the affected side as much as possible in everyday life as well as for gaming. Based on our findings, we designed three interaction techniques with varying levels of secondary hand involvement, allowing for different distributions of interaction responsibilities between the primary and secondary or affected hand.

To evaluate the interaction techniques, we assessed their usability and efficiency in comparison to one-handed interaction with a single motion controller, leading to our first research question:

RQ2.2.1 *How do the proposed inclusive bimanual interaction techniques differ in usability and efficiency?*

To address this research question, we conducted a user study with 26 participants without upper limb differences. Building on these findings, we then developed alternative input methods that enabled the use of the affected side for pointing, confirming, or both. This led to our second research question:

RQ2.2.2 *How do people with upper limb differences assess different levels of responsibility of the secondary hand?*

To answer RQ2.2.2, we conducted an additional user study with four participants with unilateral upper limb differences.
In the first phase of this iterative user-centered design process [37, 119], we conducted an interview with a single experienced participant to learn about his experience with PC and gaming console usage. Although this may reduce the generalizability of the findings and increase the risk of bias in early design iterations, the subsequent iterations of the user-centered design process will involve a broader audience, including three additional participants with unilateral limb differences. This approach is expected to strengthen the validity of our findings by incorporating diverse perspectives and refining the design based on broader user feedback [118].

The contribution of this work can be summarized as follows:

- An inclusive user-centered design approach for bimanual interaction techniques in VR.

- The development of three bimanual interaction techniques using EMG and motion tracking, along with a comparative user study evaluating their usability and efficiency.
- Insights from four individuals with upper limb differences, assessing the role and involvement of the secondary hand in VR interactions.
- Guidelines for future accessible VR developments, with a focus on designing for users with unilateral upper limb differences.

The work is structured as follows: Section 11.2 reviews related work on bimanual interaction, adaptive hardware, and VR accessibility for users with upper limb differences. Section 11.3 details the materials, methods, and user-centered design approach used to develop the interaction techniques. Section 11.4 presents the design process, including an interview with a one-handed participant who is experienced in computer and gaming console usage, a large-scale usability study, and feedback from participants with upper limb differences. Section 11.5 discusses the findings and future research directions, while Section 11.6 concludes with key takeaways and recommendations for improving VR accessibility.

11.2 Related Work

11.2.1 Adaptive Hardware and Alternative Input Systems

In the field of PC and console gaming, alternative input devices such as the Xbox Adaptive Controller[1] and Quadstick[2], are available, providing customizable configurations with external switches, joysticks, and sip-and-puff devices, allowing users with varying motor abilities to interact with digital systems [23, 51, 68]. Additionally, ergonomic one-handed keyboards and foot-operated input interfaces further extend accessibility options [7, 229, 260]. Voice-controlled interfaces and eye-tracking systems also offer viable solutions for hands-free interaction, particularly for users with severe physical disabilities [134, 173, 206]. These systems collectively expand the range of accessible input methods, enabling personalized configurations tailored to the user's motor capabilities.

11.2.2 Sensor-Based Input Systems: EMG and Motion Tracking

Emerging wearable sensor-based input systems, such as electromyography (EMG) and motion tracking, offer non-invasive alternatives for assistive technology. EMG-based systems detect muscle activity to translate neural signals into functional movements, enabling users to control devices with minimal physical effort. Many systems can provide real-time, high-fidelity muscle data, widely applied in rehabilitation, prosthetic control, and ergonomic research [181]. Research has demonstrated EMG's potential for prosthetic

[1] https://www.xbox.com/accessories/controllers/xbox-adaptive-controller
[2] https://www.quadstick.com/

adaptation and assistive interfaces, improving both digital accessibility and physical mobility for individuals with motor impairments [41, 211, 248]. Beyond EMG, motion-tracking technologies contribute to mobility solutions, rehabilitation, and assistive robotics. Such systems can be used to analyze movement patterns, providing objective insights for rehabilitation interventions [190, 240, 266]. Studies highlight the role of motion tracking in prosthetic control, enhancing precision in powered prosthetic devices, and upper limb rehabilitation [47, 231, 258]. Integrating biological and sensor-based input systems into VR accessibility solutions has the potential to redefine interaction paradigms, reducing reliance on conventional controllers and expanding usability for individuals with diverse mobility needs. As these technologies evolve, they present new opportunities for inclusive and adaptive interaction techniques in immersive environments.

11.2.3 Interaction Design Strategies and User Autonomy in VR

While sensor-based and adaptive hardware solutions expand the technical toolkit for accessibility, the design of interaction strategies in VR plays an equally critical role in shaping user experience. Yamagami et al. [275] proposed a design space for mapping unilateral input to bimanual VR interactions, demonstrating that system-assisted techniques can help compensate for physical limitations. However, their findings also revealed a significant trade-off: heavy reliance on automated assistance can diminish user autonomy, engagement, and self-efficacy. These insights underscore the importance of developing interaction techniques that are both accessible and user-driven—preserving agency and fostering meaningful engagement in immersive environments.

11.3 Materials

This section outlines the hardware design choices and the user-centered design process used in developing and evaluating the interaction techniques.

11.3.1 EMG Setup

The EMG signal was acquired using the Delsys Trigno Lite System[3] together with the Trigno Avanti Sensor[4]. The sensors were set to a mode that outputs rectified EMG data (EMG RMS, 148 sa/s RMS Update rate, 100 ms RMS window, 20-450 Hz EMG bandwidth). The participants attached the sensor to their upper arm on their secondary side in the area of the biceps with medical tape. They were then instructed to tighten the biceps without moving the arm. For classification purposes, we utilized a threshold technique. During preliminary tests, we observed the resting potential to be below 0.05 mV. Even slight contractions of the biceps usually exceeded 0.01 mV. So we set the threshold to 0.03 mV, which was easy to activate while balancing false-positive classification. During both

[3] https://delsys.com/trigno-lite/
[4] https://delsys.com/trigno-avanti/

studies, participants could practice activating the threshold and fine-tune it if necessary until they felt comfortable. The data was transferred via Bluetooth to the Trigno Lite System, which is connected via USB to the PC, running the necessary software. The data was live streamed into Unity via the API.

11.3.2 Motion Tracking Setup

There are several approaches for Motion Tracking. Most up-to-date HMDs come with built-in hand tracking technology based on 3D input, such as Pico 4[5], Varjo XR3[6] or Meta Quest[7]. These algorithms are usually optimized to detect hands with five fingers. The other hand can have tracking issues or might not be recognized at all. However, there are tracking technologies that are independent of the appearance of the tracked body part, such as marker-based tracking with infrared cameras, making it also possible to be used with diverse bodies (Guideline 1), such as motion capture systems by Optitrack[8], Vicon[9] or Qualisys[10]. These are also flexible to use, as the markers can be placed on different body parts (Guideline 2). Moreover, the markers can be small and do not require a large interaction space for the user (Guideline 7).

We used the Qualisys Miqus Motion Capture System. It provides high accuracy real-time motion tracking data. We used 9 cameras, mounted to the walls and tripods, capturing many angles to ensure the users' hands are visible to enough cameras at all times. The system is connected to the PC via LAN, and the data can be live-streamed directly into Unity via the API.

11.3.3 VR System and Computing Setup

We used the Meta Quest 3 with one motion controller. It provides a visible field of view (FoV) of 110° horizontally and 96° vertically, a 2064×2208 pixel per eye resolution, and a refresh rate of 120 Hz[11], offering a good immersive experience. We developed a VR environment using Unity[12] and OpenXR[13] for the Meta Quest. Both the EMG and the motion capture system were connected to a desktop PC (Intel Core I9 3.70 GHz, 32 GB RAM, NVIDIA GeForce RTX 3090, Windows 10 Pro). The Meta Quest was used in Link mode, enabling real-time streaming of EMG and motion tracking data into Unity, with the results displayed inside the HMD. We used the Link mode via cable to prevent lags and data dropouts due to Wi-Fi problems.

[5]https://www.picoxr.com/products/pico4
[6]https://varjo.com/products/varjo-xr-3/
[7]https://www.meta.com/quest/
[8]https://www.optitrack.com/
[9]https://www.vicon.com/
[10]https://www.qualisys.com/
[11]https://vr-compare.com/headset/metaquest3
[12]https://unity.com/
[13]https://www.khronos.org/openxr/

11.4 User-Centered Design

We followed a user-centered design process, similar to [104], based on the process model of human-centered design as defined in ISO 9241-210[14]. In the first step in this work, we invited a person with unilateral limb differences to share their experience with gaming and PC usage and their wishes and ideas for VR input methods. From the results, we derived concepts for novel VR interaction techniques. To evaluate the interaction techniques, we conducted two studies: first, we tested the interaction methods in terms of usability and efficiency with a broad audience. Additionally, we invited four participants with unilateral limb differences to provide feedback.

11.4.1 Initial Data Acquisition and Development of the User Interfaces

This section describes the first phase of the user-centered design process, where we focused on understanding user needs and gathering insights.

11.4.1.1 Methodology

To achieve this, we conducted a semi-structured interview with a person with unilateral upper limb differences to learn about his habits and preferences when using PCs and gaming consoles.

The interview aimed to understand how individuals with unilateral limb impairments interact with conventional input devices (e.g., keyboard, mouse, controllers), the challenges they encounter, and potential strategies to overcome them. Additionally, we explored the participant's insights on how the position of the affected limb could be effectively visualized in VR. In this exploratory phase of our research [101], our objective was to gather in-depth qualitative insights that could inform the design of our prototypes and provide valuable initial guidance for our project. The data was analyzed in a content analysis approach, using inductive coding. Based on our findings, we developed three interaction techniques.

We recruited one male participant (P1) through personal contact. He is a computer science student with experience in both PC and console gaming and has previously used a VR HMD. His background provided a strong foundation for the user-centered design process, as he could offer insights not only from an end-user perspective on accessibility in PC and gaming environments but also from a technical standpoint, given his expertise in hardware and software capabilities.

This also aligns with the recommendation by Kruse et al. [147], which emphasizes the importance of involving experienced users in the evaluation process. Since first-time VR users may struggle to identify design flaws due to the novelty of the technology, selecting a participant with prior exposure to VR ensures more informed feedback, leading to a more effective assessment of accessibility challenges. Further demographic details can be found in Table 11.2.

[14] https://www.iso.org/standard/77520.html

Questions were designed to elicit information on the participant's daily use of input devices (e.g., keyboard, mouse, controllers, VR systems), his strategies for interacting with both conventional and VR systems, and the challenges he faced in various contexts. Additionally, we explored his preferences for avatar representations, control schemes, and feedback mechanisms in VR environments. The participant was encouraged to discuss his ideal VR experience, with particular attention to how control systems could be made more accessible for users with upper limb differences. Furthermore, we explored the participant's insights on how the position of the affected limb could be effectively visualized in VR. To ensure thorough documentation, the interviews were audio-recorded and later transcribed for analysis.

11.4.1.2 Summary of Interview Results

The interview provided insights into the participant's adaptations in gaming due to unilateral upper limb differences. He primarily uses a keyboard with his affected left hand and a right-handed mouse, remapping controls for better usability, such as enhancing functions near the WASD keys and using a mouse with numerous programmable keys. Despite extensive experience with gaming, he faces challenges with devices like the Nintendo Switch, notably in Mario Kart, where control remapping is not possible, restricting the level of control he can have in the game.

Regarding VR, he expressed frustration with two-handed setups, as he could only utilize one control option in shooter games, limiting his gameplay experience. He also emphasized a desire for more customizable control options and locomotion methods in VR systems.

Overall, the participant seeks adaptable control schemes and clear feedback mechanisms in both traditional gaming and VEs. Moreover, the interview included the possibility for the participant to try out the EMG system. He was asked to try out different muscles on his affected arm that seemed suitable for him to use for VR interaction. The signal strength was visible on a monitor. He preferred using the biceps, as it balances ease of use and signal strength for him. Additionally, he stated to like abstract or creative avatars over realistic ones.

11.4.1.3 Conclusion

In summary, it can be concluded that a focus on flexible control schemes, adaptability, and intuitive input methods is crucial for users of VR systems. The participant's desire for individual customization indicates that users increasingly expect to tailor their control experiences to personal needs and preferences. The preference for abstract or creative avatars suggests that realistic representations in VR may not appeal to every user, particularly due to the uncanny valley effect. Furthermore, the selection of the biceps as the preferred method for interaction in VR underscores the importance of efficiency in input methods for such applications. These insights can assist developers and designers in adopting user-centered approaches and enhancing accessibility and user experience in future VR systems.

Insights related to upper-limb use in gaming/VR have inspired the development of interaction techniques (e.g., mapping all functions onto one hand is used as a comparative condition, as it appears to be a viable alternative to the presented EMG/tracker interaction). Other responses represent subjective opinions or individual user behaviors and will therefore not be directly incorporated into the design. Instead, various hand visualizations will be developed, which will later be tested with four participants.

11.4.1.4 Design of Interaction Techniques

Our design was guided by the central question: *What role should the secondary hand play in VR?* To explore this, we employed motion tracking for pointing and EMG signals for confirmation, investigating three distinct techniques. The first technique relied solely on motion tracking for pointing on the affected side, allowing users to interact through hand movements. The second technique focused exclusively on EMG-based confirmation, enabling interaction through muscle signals. The third technique combined both motion tracking and EMG confirmation on the affected side, aiming to balance precision and usability. By evaluating these techniques, we sought to determine the most effective method for enhancing accessibility and interaction in VR environments.

To systematically evaluate these techniques, we defined four interaction conditions, each varying the role of the secondary hand in VR interaction:

- **Condition 1 (Control Condition): No responsibility for secondary hand.** This baseline condition leverages the participant's preference for customization and their ability to remap controls for efficiency. Since the participant is already comfortable using one hand for control in conventional gaming setups, this condition ensures that the primary hand can take on full control responsibilities. The inclusion of button remapping mirrors the participant's approach in PC gaming, allowing them to optimize their control scheme without relying on the secondary hand. This condition serves as a starting point for comparison against the other, more complex configurations. Figure 11.1a shows a participant experiencing this condition.

- **Condition 2: *Confirming* responsibility for the secondary hand.** In this condition, the secondary hand is responsible for selection tasks using an EMG system, while the primary hand handles pointing; see Figure 11.1b. Based on the participant's openness to new technologies, this condition introduces EMG control as a muscle-based input system for the secondary hand.

- **Condition 3: *Selecting* responsibility for the secondary hand.** For targeting tasks, this condition incorporates a motion tracking system, allowing the secondary hand to control motion in the VR environment; see Figure 11.1c. Since the participant has experience with precision-based tasks in gaming, such as targeting in shooters, this condition caters to their need for responsive and accurate control. The motion tracking system offers fine-tuned motion tracking, which aligns with the participant's preference for fluid and adaptive control. Meanwhile, the primary hand is responsible for confirming.

- **Condition 4: *Confirming and Selecting* responsibility for the secondary hand.** This most advanced condition assigns full responsibilities—both targeting and selection—to the secondary hand using a motion tracking system and an EMG system for muscle-based input; see Figure 11.1d. Drawing from the participant's desire for more control options and customization in VR, this condition provides a comprehensive interface that allows the secondary hand to fully participate in the VE, offering a more empowering experience.

11.4.2 Usability and Efficiency Study

In the context of universal design, we investigate the novel interaction techniques in terms of efficiency and usability and to locate and eliminate possible design errors. For that, we invited 26 student participants to test the interaction techniques. We did not limit the participants to people without upper limb differences to get feedback from a broader audience, including people with VR experience. This way, we will be able to present a more refined prototype in the third stage of this user-centered design, where we will especially focus on feedback from a user group of people with unilateral limb differences, who will then be able to focus on user-specific opinions.

11.4.2.1 User Study Setup

The virtual version of the Quest controller in the primary hand was always visible in VR. When the motion tracking was used, a gray ray was visible, with its origin spatially registered to the position of the marker on the (secondary) lower arm. If motion tracking was not used, the ray was attached to the VR controller in the primary hand. The EMG sensor was not visualized in the VE. The setup for right-handed participants can be seen in Figure 11.2.

We designed a two-part task: i) a primary task, requiring higher dexterity, that was always done with the primary hand, and ii) a secondary task with less dexterity required, with different levels of responsibility for the secondary hand. The primary task required participants to manipulate a virtual sphere through a pipe using a virtual pen. The color of the ball changed regularly and could only be moved if the color of the pen matched the ball color. The color could be changed by pointing towards the corresponding color panel (either with the controller or with a motion-tracked arm, depending on the condition), and the selection was confirmed by either button pressing on the controller or tensing the biceps with the EMG sensor. The four conditions are described in detail in the following:

- ***C*** In the *Controller-only* condition, all input was done using the VR controller in the primary hand. In the VE, participants grabbed the pen and moved the ball with it.

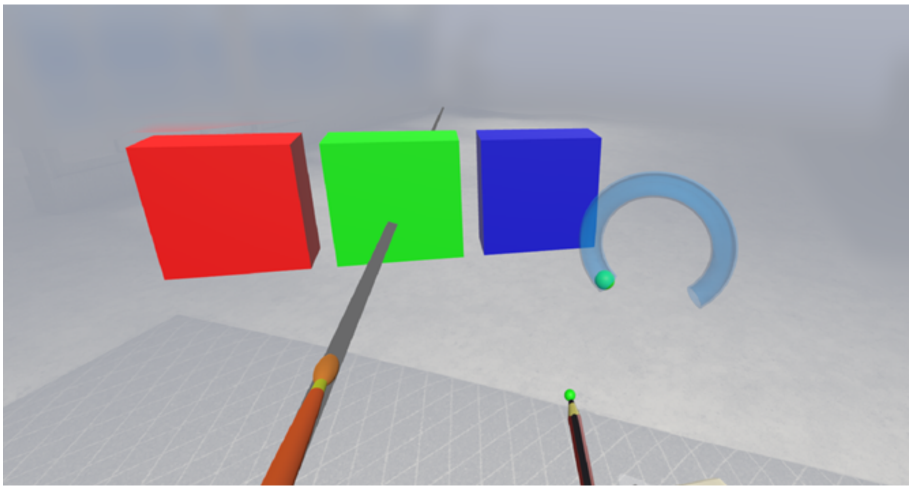


Figure 11.2: Participant view of a right-handed person in the *EMG + MT* condition.

When they wanted to change the color, they could keep the pen gripped. They then pointed towards the desired color panel and used the trigger button to select the color.

- ***C + EMG*** In the *Controller + EMG* condition, participants grabbed the pen and moved the ball with it using the controller in the primary hand. For color selection, they pointed to the color panel with the controller, but to confirm the selection, the biceps of the secondary arm had to be tensed.

- ***C + MT*** In the *Controller + Motion Tracking* condition, participants grabbing the pen and moving the ball with it was again done using the controller in the primary hand. Color selection was done by pointing towards the desired color with the secondary arm, and confirming the choice was done using the trigger button of the controller.

- ***EMG + MT*** In the *EMG + Motion Tracking* condition, operating the pen to move the ball was done by the controller in the primary hand. Color changing now was done entirely by the secondary side, using motion tracking to point to the color panel and EMG to confirm the selection.

We used 8 different tubes with different levels of curvature. Each appeared twice in each condition, resulting in 16 trials per condition. The virtual setup was adjusted to fit the handedness of the participant. The pen initially appeared closer to the primary side of the participant, and the color selection panel appeared on the contralateral side, facing toward the user's head at a 45-degree angle. This ensured that for the conditions including motion tracking (on the secondary hand), the hand would not interfere with the primary hand holding the pen. The ball always appeared on the left side of the tube and ended on the right side.

We chose a within-subjects design with four conditions (***C***, ***C + EMG***, ***C + MT***, and ***EMG + MT***). Conditions were counterbalanced using Latin Square.

11.4.2.2 Hypothesis

Researchers have shown that bimanual interaction can be more efficient than unimanual interaction [166]. Furthermore, there is an indication that people prefer bimanual over unimanual interaction [255]. We developed three novel bimanual interaction techniques based on EMG and motion tracking. We hypothesize that the interaction techniques will have better usability and efficiency compared to unimanual interaction. However, due to the novelty and unfamiliarity of the system and the used technology, especially EMG, we suspect to see increased mental and physical demand, while we expect the other sub-scales of NASA TLX to be improved. Our hypotheses are the following:

H1 Task Completion Time of ***C + EMG and C + MT and EMG + MT*** is lower compared to ***C*** because people are used to working with both hands simultaneously.

H2 Usability of ***C + EMG and C + MT and EMG + MT***is better compared to ***C*** because people prefer bimanual over unimanual task completion [255].

Regarding the sub-scales of NASA TLX, we do not expect a trend in task load in general, because we expect some subcomponents to develop in different directions, such that the final task load score might have a similar magnitude but a different composition.

In particular, we hypothesize:

H3a Mental Demand is higher for the three proposed interaction techniques compared to unimanual interaction.

H3b Physical Demand is higher for the three proposed interaction techniques compared to unimanual interaction.

H3c Temporal Demand is lower for the three proposed interaction techniques compared to unimanual interaction.

H3d Performance increased for the three proposed interaction techniques compared to unimanual interaction.

H3e Effort decreased for the three proposed interaction techniques compared to unimanual interaction.

H3f Frustration decreased for the three proposed interaction techniques compared to unimanual interaction.

11.4.2.3 Participants

We invited 26 participants via the student participant pool, 7 female and 19 male. Participants received either financial compensation or study credits, as they wished. 8 participants were in the age group 18-24, 16 in the age group 25-34, and 2 in the age group 35-44. Three participants were left-handed, and 23 were right-handed. None of them had upper limb differences.

11.4.2.4 Procedure

After giving informed consent, participants filled out the demographic part of the questionnaire. The EMG sensor was attached to their biceps on the secondary arm, and they could see the signal of the EMG sensor on a monitor in front of them and practice the activation. They were given as much time as necessary to practice flexing the biceps to produce a short signal. Then, also, the tracker of the motion tracking system was attached to their lower arm on the secondary side. The participants then were asked to put on the HMD and get familiar with the task environment. In each condition, the task was explained, and the participants could ask questions and practice the task until they felt ready to start. They then proceeded through 16 trials. After each condition, the participant answered the System Usability Scale [130] and the NASA Task Load Index [103].

11.4.2.5 Results

We evaluated the interaction techniques in terms of efficiency by measuring task completion time, usability with the System Usability scale [130] and task load via the NASA TLX [103] and present the results and analysis in the following.

Task Completion Time For analyzing the task completion time results, we calculated the sum of all 16 trials per condition for each participant. According to a Shapiro-Wilk test and inspecting the QQ-plot, we found that the normality assumption for residuals was not met. We analyzed the data with the Friedman test and found a statistically significant difference in task completion time between the four tested input methods $\chi^2(3) = 41.585, p < .001$. A pairwise Wilcoxon signed-rank test with Bonferroni correction indicated that task completion time was significantly higher for ***C* + *EMG*** compared to ***EMG* + *MT*** ($Z = -4.330, p < .001$), ***C*** ($Z = -4.153, p < .001$), and ***C* + *MT*** ($Z = -4.432, p < .001$), see Figure 11.3. None of the other pairs revealed a significant effect.

Usability Shapiro-Wilk test and inspection of the Q-Q plot showed that the normality assumption was met. A one-way repeated measures ANOVA was performed to compare the effect of the input method on system usability. We found a significant difference between at least two groups ($F(3,75) = 27.773, p < .001, \eta_p^2 = .526$). Post-hoc test using Bonferroni correction indicated a significantly lower SUS score for ***C* + *EMG*** compared to ***C*** ($p < 0.001$), ***C* + *MT*** ($p < 0.001$) and ***EMG* + *MT*** ($p < 0.001$). Moreover, ***C*** and ***EMG* + *MT*** were significant ($p < .05$) with ***C*** achieving higher scores; see Figure 11.4.

Task Load We evaluated the NASA TLX [103] results for each of the six sub-scales. The mean and SD values can be found in Table 11.1.

According to the Shapiro-Wilk test and inspecting the QQ-plot, we found that the normality assumption for residuals was not met in all cases. Analysis of the data with the Friedman test showed a significant effect for interaction method on each sub-scale (Mental Demand: $\chi^2(3) = 13.74, p = .003$, Physical Demand: $\chi^2(3) = 21.23, p < .001$. Temporal Demand: $\chi^2(3) = 17.44, p = .001$, Performance: $\chi^2(3) = 31.89, p < .001$, Effort: $\chi^2(3) = 29.57, p < .001$, Frustration: $\chi^2(3) = 36.16, p < .001$).

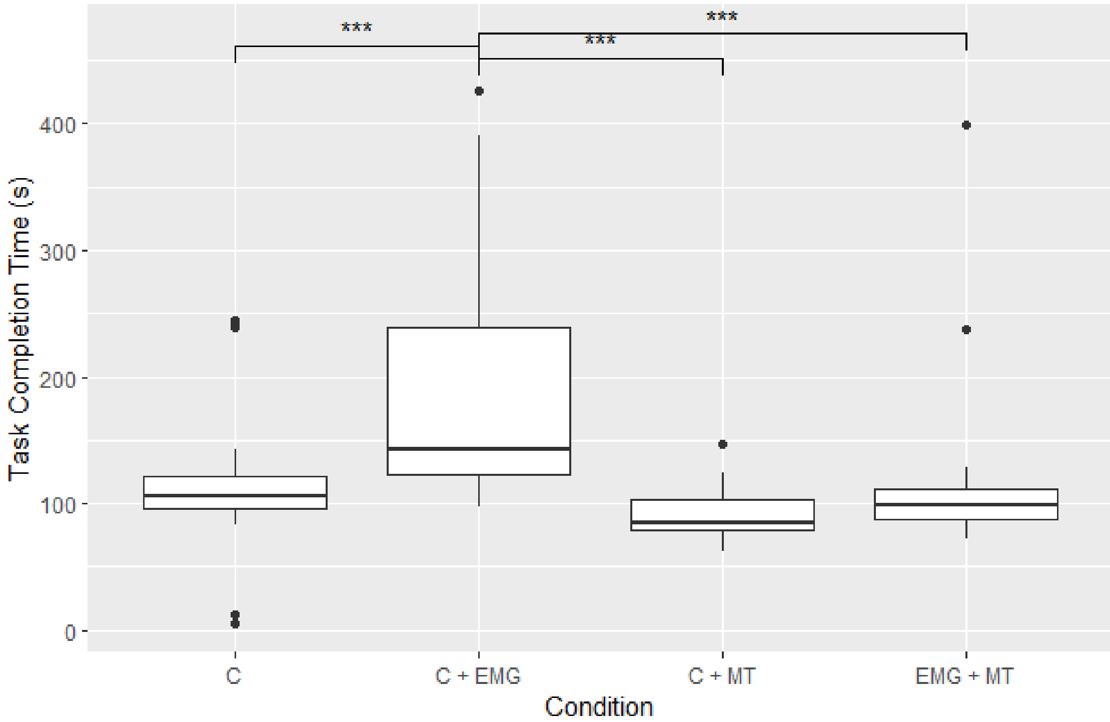


Figure 11.3: Task completion times for all conditions. ***: p < 0.001, **: p < 0.01, *: p > 0.05.

Post-hoc tests with Bonferroni correction revealed significant differences between interaction methods in each NASA-TLX sub-scale, as listed in Table 11.1.

11.4.2.6 Discussion

In the following, the findings on task completion time, usability, and task load for the three proposed interaction techniques are discussed in detail.

Task Completion Time We found that ***C + EMG*** had a significantly higher task completion time than all other tested interaction methods. For some trials, it took participants longer than three seconds to change color successfully. Although participants could practice tensing the muscle beforehand, some faced challenges during the experiment to successfully reach the necessary activation level. This usually happened in the first and last trials, showing that it needs more practice time to learn how to activate the muscle, as well as that it is a physical activity that is tiring for the muscle. However, the same issue also appeared in ***EMG + MT***, which had task completion times in a similar range as ***C*** and ***C + MT***, indicating that successfully activating the EMG signal was not the main problem in ***C + EMG***.

We also noticed participants accidentally changing color after setting the color correctly because they moved the primary hand back to the sphere in the pipe on the shortest path, which was, for some colors, crossing other colors. The threshold we used to simulate a "pressed button" signal was determined from the prototyping phase. It was set relatively

Table 11.1: Mean and standard deviations (SDs) of the NASA-TLX questionnaire and statistical comparisons

Metrics	C	C + EMG	C + MT	EMG + MT	Significance
Mental demand	27.3 (15.2)	48.1 (27.4)	29.6 (23.2)	38.7 (27.0)	***C*** and ***C + EMG*** ($Z = -3.399, p = .004$) ***C + EMG*** and ***C + MT*** ($Z = -2.965, p = .018$)
Physical demand	30.8 (26.0)	48.8 (27.0)	32.5 (24.7)	46.2 (29.0)	***C*** and ***EMG + MT*** ($Z = -2.762, p = .034$) ***C + EMG*** and ***C + MT*** ($Z = -2.749, p = .036$) ***C + MT*** and ***EMG + MT*** ($Z = -2.749, p = .036$)
Temporal demand	42.5 (23.5)	53.5 (25.5)	33.7 (24.1)	43.1 (26.2)	***C + EMG*** and ***C + MT*** ($Z = -3.180, p = .009$)
Performance	23.1 (22.2)	45.4 (23.8)	23.3 (22.5)	23.1 (15.4)	***C*** and ***C + EMG*** ($Z = -3.998, p < .001$) ***C + EMG*** and ***EMG + MT*** ($Z = -4.052, p < .001$) ***C + EMG*** and ***C + MT*** ($Z = -3.920, p < .001$)
Effort	34.4 (25.5)	58.7 (25.1)	37.3 (25.0)	46.9 (25.7)	***C*** and ***C + EMG*** ($Z = -4.008, p < .001$) ***C + EMG*** and ***EMG + MT*** ($Z = -2.908, p = .022$) ***C + EMG*** and ***C + MT*** ($Z = -4.268, p < .001$) ***C + MT*** and ***EMG + MT*** ($Z = -2.849, p = .026$)
Frustration	24.4 (19.6)	49.8 (31.4)	20.6 (20.3)	28.5 (24.6)	***C*** and ***C + EMG*** ($Z = -3.894, p < .001$) ***C + EMG*** and ***EMG + MT*** ($Z = -3.658, p = .002$) ***C + EMG*** and ***C + MT*** ($Z = -4.113, p < .001$)
Sum	182 (103)	304 (132)	177 (99.9)	226 (120)	***C*** and ***C + EMG*** ($Z = -3.338, p = .005$) ***C + EMG*** and ***C + MT*** ($Z = 3.377, p < 0.005$)

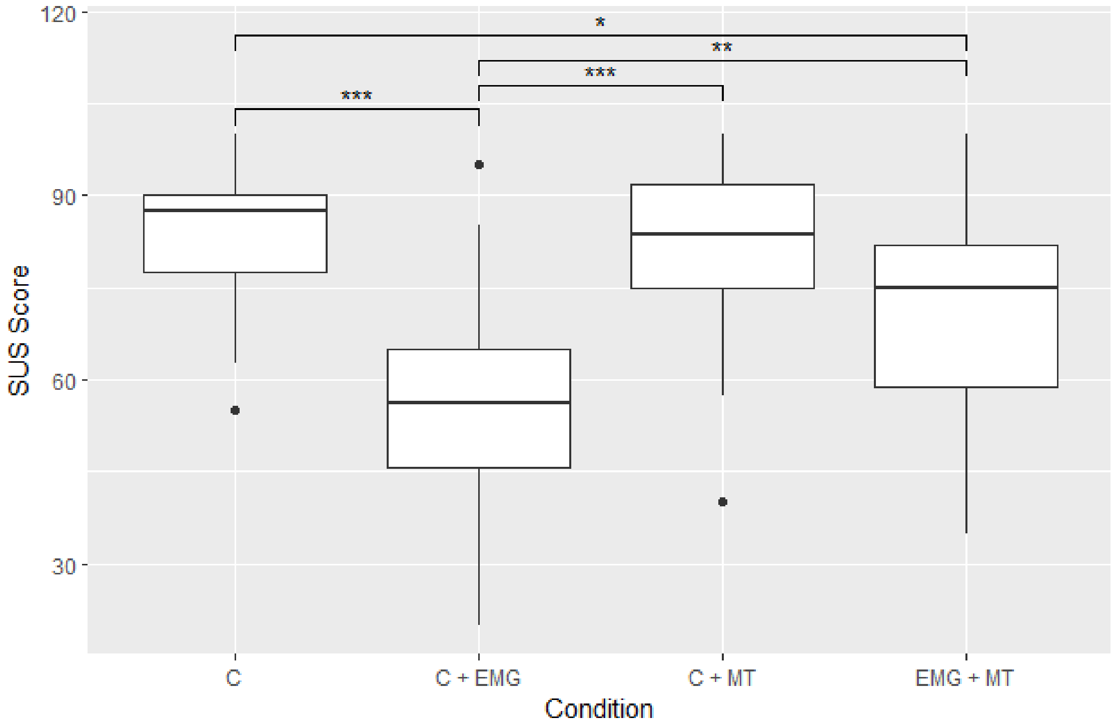


Figure 11.4: System Usability Scale scores for all conditions. ***: $p < 0.001$, **: $p < 0.01$, *: $p > 0.05$.

low so that everyone was able to activate the threshold. Some participants seemed to need more time to relax the muscle again than others. So perhaps a different algorithm than the simple threshold approach would have been necessary for this interaction method. We observed two techniques that participants developed to avoid this. First, many participants tried not to move the ray over or through the other color panels when moving back to the sphere. This seems to lead to a higher task completion time. Furthermore, some participants just waited for the color of the ball to change to the current color of the pen. This indicated that people feared not being fast enough with changing the color anyway, so they thought waiting for an unknown amount of time (the next color was selected randomly) was the better option. It could also show that it was too much work to activate the muscle.

Interestingly, task completion time in the other interaction method, including EMG (***EMG + MT***) was significantly lower than in ***C + EMG***. Here we could observe the users' strategy to just keep the motion tracking pointer directed onto the color panel according to the current ball color. This was possible because here the division of the tasks between both sides allowed one hand to stay on the pipe and the other to stay on the color panel.

Although we did find shorter task completion times in ***EMG + MT*** compared to ***C + EMG***, our findings do not support H1. All interaction methods seem to have task completion times in a similar range, except for ***C + EMG*** with the problem of the still activated muscle discussed above.

People are seemingly quite efficient with one controller only. This might be related to the training effect with the use of a mouse cursor, where also sequential tasks are usual in everyday tasks. It is interesting to see that the use of new technologies can reach a similar level without much practice in two of three novel interaction methods.

Usability The SUS data shows a similar pattern: EMG performs worse than the other conditions, which fits with our observations discussed above. Due to activation and deactivation issues, the condition was harder than the others, which is also reflected in the SUS score. Again, in the other condition with EMG, the deactivation was not an issue because it was possible to keep the ray on the color panel and operate the pen with the controller. Here, however, also a significant difference between ***C*** and ***EMG + MT*** was found, with lower usability scores for ***EMG + MT***. This might be due to the still quite hard activation of the color panel. The data partly supports our hypothesis, with novel technologies ***C + EMG*** and ***EMG + MT*** having lower usability ratings than C. However, ***C + EMG*** and ***C + MT*** were different, although having a similar level of responsibility for the hands in both cases. This indicates that motion tracking per se is more easily usable without much practice than EMG.

Task Load In all sub-scales of NASA TLX, at least one combination of ***C + EMG*** with another condition was significant in a way that ***C + EMG*** performed worse than some other condition. This is also the case in the summed up score: Here, ***C + EMG*** had a significantly higher task load than ***C*** as well as ***C + MT***.

- *Mental Demand:* **H3a** cannot be confirmed. Although ***C + EMG*** had a significantly higher Mental Demand than ***C***, ***C + MT*** and ***EMG + MT*** did not, indicating difficulties in the condition ***C + EMG***.

- *Physical Demand:* **H3b** can be partly confirmed, with significantly higher ratings for Physical Demand for ***EMG + MT*** compared to ***C*** as well as ***C + MT***. Interestingly, it seems to make a difference for Physical Demand, whether the secondary arm is used only for motion tracking or for motion tracking and EMG, indicating that EMG is perceived to be more physically demanding than the corresponding button press on the controller in ***C + MT***.

- *Temporal Demand:* **H3c** cannot be confirmed, as no pairs including ***C*** were significantly different.

- *Performance:* **H3d** cannot be confirmed, as no pairs including ***C*** were significantly different. Interestingly, ***C + EMG*** received the significantly highest performance ratings among all four conditions, indicating a higher feeling of failure in that condition. So we assume that actually ***C + EMG*** had the worst performance ratings.

- *Effort:* **H3e** cannot be confirmed. ***C + EMG*** was rated significantly higher in terms of Effort than all other categories, including ***C***. Moreover, ***EMG + MT*** was rated more effortful than ***C + MT***, indicating that using EMG adds a layer of complexity to the system.

- *Frustration:* **H3f** cannot be confirmed, as ***C + EMG*** received significantly higher Frustration ratings than all other conditions.

11.4.3 Feedback from Users with Upper Limb Differences

We invited four participants with unilateral impairments of the upper limb to provide feedback in a semi-structured think-aloud process. This evaluation provides valuable insights into which interaction methods are most accessible, effective, and user-friendly for users with upper limb differences.

11.4.3.1 User Study Setup

The technical setup, including the design of the four conditions, was similar to 11.4.2. To allow for a more free exploration of the interaction techniques, we simplified the game: only one type of tube was used, and participants were asked to freely move the ball through the tube back and forth. The ball also changed its color and was moved with the pen but could also be moved if the colors did not match, unlike in the first experiment. Users gained one point per second when the pen color and ball color were equal and touched. The score was displayed on a panel in VR. Participants explored each condition for about two minutes. Furthermore, different from Study 1, the users' secondary hand was not visualized at all to avoid drawing attention away from the interaction mechanics.

11.4.3.2 Participants

The study involved four participants, from the age group 25-34, all of whom had unilateral upper limb impairments (see 11.2) from birth or early childhood. Among the four participants was participant P1, who also participated in the initial interview, presented in Section 11.4.1. Three were male, and one was female. One male participant had a missing left hand, while another experienced right-hand and arm spasms caused by meningitis during infancy. A third male participant had symbrachydactyly, resulting in limited finger development and no functional grasp. The female participant had a missing right hand. Regarding their experience with VR systems, three participants reported using VR less than once a year, while one participant reported using VR approximately once a year.

11.4.3.3 Procedure

The study began with a briefing on the objectives, consent, and a pre-test questionnaire to collect demographic data and prior VR experience. The participants then were asked

Table 11.2: Participant details.

ID	Gender	Age	Condition	VR experience
P1	male	25-34	Left hand missing	Less than once a year
P2	male	25-34	Right-hand and arm spasms	Less than once a year
P3	male	25-34	Symbrachydactyly right-sided	Less than once a year
P4	female	25-34	Right hand missing	Once a year

Table 11.3: Order of conditions.

A	B
C	***C***
C + EMG	***C + MT***
C + MT	***C + EMG***
EMG + MT	***EMG + MT***

to put on the HMD and get familiar with the task environment. From the larger-scale usability study, we learned that participants need to understand the task on the one hand and also get familiar with the used sensor technologies. So for this evaluation, we decided to have the baseline condition ***C***, with only the controller in the primary hand and no additional sensors involved, as the first condition, as many people have used some kind of controller before and thus can focus on the task itself. Moreover, we decided to have the condition including both sensors and the controller as the last condition (***EMG + MT***) to ensure both sensor technologies have been experienced before in the according conditions before combining both. So we had two orders of conditions A and B, which can be seen in Table 11.3. Two participants conducted order A, and two conducted order B.

Both the EMG sensor and the motion capture marker were only attached when it was necessary for the current condition and removed afterward to provide the most realistic experience for each prototype. As in the first study, the EMG sensor was always attached to the biceps of the secondary arm, and the motion tracker marker was attached to the lower arm of the secondary side.

Participants were given as much time as necessary to practice each condition before they could freely explore each condition for up to 2 minutes. After completing each condition, participants provided immediate feedback through verbal interviews and SUS [130] and NASA-TLX [103] questionnaires, discussing usability, comfort, and physical effort. In these interviews, participants reflected on their experiences in each condition, offering detailed insights into specific challenges and preferences. After all interaction techniques were completed, participants took part in a final interview where they compared the different techniques, provided suggestions for improvement, and shared their preferences. Subsequently, the participants were asked to put on the HMD again, and 3 different visualization options for the secondary hand (see Figure 11.5) were shown to them one by one. The participants then shared their preferences for the visualization of the secondary hand related to these choices or provided any other suggestions they had.

Figure 11.5: Suggested visualizations for the secondary hand. From left to right: White motion controller, black motion controller, wand.

11.4.3.4 Data Collection and Analysis

The qualitative data were collected through semi-structured interviews. These interviews were designed to be open-ended, allowing participants to freely discuss their experiences. The analysis employed a thematic approach, in which the transcribed interview data were systematically coded by two experimenters to identify key topics, challenges, and preferences articulated by participants. The resulting codes were then grouped into broader themes that captured recurring patterns and critical insights.

11.4.3.5 Results

We analyzed the data in terms of usability and task load and performed a reflexive thematic analysis [32] of the users' feedback.

Usability and Task Load Results The average SUS score was 71.88 (SD = 14.40), indicating moderate usability of the overall setup. Table 11.4 shows the NASA-TLX results for each of the four conditions on all subscales.

Using condition **C** as a baseline, the results show that **C + EMG** increases mental, physical, and temporal demands and effort but reduces frustration, indicating a trade-off between workload and user comfort. Meanwhile, **C + MT** enhances perceived performance substantially but slightly increases mental and temporal demands without significantly raising physical demand. The combination of **EMG + MT** effectively balances workload by reducing effort and frustration while sustaining high physical and temporal demands, although it entails greater costs in these areas compared to the baseline.

Thematic Comparison Across Conditions The study's evaluation provided valuable insights into how users adapted to and perceived each condition, highlighting both challenges and positive experiences. The following subsections explore these interactions, focusing on user feedback, to compare the different techniques and identify areas for improvement in the design of interaction methods for individuals with upper limb differences.

Table 11.4: Mean and standard deviations (SDs) of the NASA-TLX questionnaire.

Metrics	C	C + EMG	C + MT	EMG + MT
Mental Demand	30 (26.46)	45 (26.77)	41.25 (37.28)	27.5 (15.00)
Physical Demand	20 (10.80)	51.25 (39.87)	27.5 (6.45)	43.75 (19.31)
Temporal Demand	11.25 (16.01)	23.75 (21.36)	22.5 (13.23)	17.5 (6.45)
Performance	13.75 (10.31)	16.25 (8.54)	42.5 (31.22)	13.75 (11.81)
Effort	30 (12.91)	48.75 (31.19)	28.75 (14.93)	23.75 (4.79)
Frustration	36.25 (27.80)	21.25 (19.31)	38.75 (17.02)	16.25 (7.50)

User Experience: Across the different conditions, users' experiences evolved as they adapted to the various tasks and controls. In ***C***, although the initial learning curve for understanding the controller and grip function was steep, users eventually found the controls simple and satisfying. One remarked, "Once you have understood this to some extent and tried it out a bit, then it was quite simple to use." In ***C + EMG***, users appreciated the innovative approach of using both arms for different inputs and found the sensor's small and unobtrusive design appealing. One user noted, "The cool thing is that you somehow don't even notice the sensor. It's small and light and not bulky." *The novelty of independent inputs for each arm made the experience more engaging. However, some users encountered difficulties with muscle tension and coordination, with one explaining, "I had a bit of a problem with relaxing my arm again."* ***C + MT*** introduced issues with the beam direction and intuitive control, making the experience feel less fluid than in previous conditions. One user commented that "the problem was that it was pointing in the wrong direction, and it was a bit unintuitive." However, using both hands for different tasks was still considered a positive aspect. Users enjoyed the cognitive challenge of dividing attention between tasks, with one noting, "It was fun because I could split the task more efficiently." Yet, this condition was physically more demanding, as users found it strenuous to keep their arms raised for extended periods. In ***EMG + MT***, users found the experience smooth and enjoyable, particularly appreciating the novelty of performing distinct tasks with each arm. One participant likened it to playing drums, saying, "It felt a little bit like I had two hands, like when playing drums, where each hand has a different rhythm." Despite the fun and ease of use, muscle tension remained a challenge, especially for users with less-developed muscle groups. One user pointed out, "Muscle tension is still not for me the go-to remedy," underscoring the physical difficulty of controlling the game through muscle contraction. In sum, while the user experience improved with each condition and users adapted more effectively, challenges related to physical effort, coordination, and muscle fatigue persisted, revealing key areas where further refinement could enhance both comfort and ease of use.

Learning Curve and Adaptation: The learning curve and adaptation varied notably across the different conditions, with users gradually becoming more comfortable and efficient as they progressed. In ***C***, users found the initial challenge to be understanding how the gripping function worked and which buttons on the controller were responsible for specific actions. One user explained, "Once you have understood this to some extent and tried it out a bit, then it was simple to use." While the learning curve was steep at first, practice allowed them to gain familiarity with the controls, making the task manageable over time. In ***C + EMG***, users found the experience required more adjustment. They commented that "it takes a bit more getting used to... so that you can do it more precisely." The primary challenge was mastering the precision of inputs, particularly understanding when the pressure or impulse was sufficient. This indicates that while the task was easy to grasp conceptually, it required ongoing practice to refine and perfect the control mechanics. ***C + MT*** posed even more difficulty in the beginning, as users expressed that "at the beginning it was much more difficult... towards the end it was a bit more familiar." While users found some aspects of the control system intuitive after initial use, the challenge lay in coordinating both buttons efficiently and accurately. One participant noted that "it was a bit of a challenge against yourself to get it right and quickly with both buttons," highlighting the increased cognitive and physical demands compared to earlier conditions. By ***EMG + MT***, the learning curve was smoother and more intuitive. Users acknowledged that practice led to greater proficiency, stating, "If you learn it again, you're probably faster. But it's another learning curve. You have to get used to it, but it works." The EMG sensor, which initially caused skepticism in earlier conditions, was described as much easier to use in this context. One user remarked, "It was just so much easier; it worked much better." This suggests that the system improved in intuitiveness as users practiced, leading to a more seamless and fluid experience. In summary, while ***C*** required users to overcome the steepest initial learning curve, ***C + EMG*** and ***C + MT*** introduced precision and coordination challenges that took time to master. By Condition ***EMG + MT***, users found the experience more intuitive and easy to adapt to with practice, highlighting an overall progression in user adaptability and efficiency across conditions.

Suggested Improvements and Technical Difficulties: Users provided various suggestions and improvements across the conditions, reflecting their evolving understanding of the system and preferences for optimizing the experience. In condition ***C***, emphasis was placed on the need for more ergonomic hand positioning that mimics real-life tasks, with one user stating, "The hand position would have been more ergonomic or more similar to real life." In ***C + EMG***, feedback and threshold settings were crucial, with a participant suggesting that better haptic feedback would enhance the experience. Users also found it unnatural to use their biceps for gaming input and highlighted the need to lower the threshold for triggering actions to make tasks less physically taxing. Suggestions in ***C + MT*** focused on fine-tuning the control system's layout, with users proposing adjustments such as moving the controls "further to the left and further down." One imaginative suggestion involved adding dynamic elements, like "having a machine gun on my right shoulder." In ***EMG + MT***, while users appreciated the ease of use, they proposed starting with both hands simultaneously for a smoother experience and acknowledged the importance of properly setting thresholds for fluidity. Overall, participants pointed to the need for ergonomic adjustments, better feedback systems, and optimized threshold settings to improve usability. However, technical and operational issues impacted the user experience across several conditions. In ***C***, users reported technical problems, including complete picture freezes and instances of lagging, creating frustration and interrupting task flow. Comments like "Now it is stuck" highlighted the system's unreliability. In ***C + EMG***, although users encountered fewer outright failures, they faced issues with the EMG sensor, which lacked the tactile feedback and speed of traditional buttons. One participant noted that the impulse required to trigger responses took longer than intended, affecting fluidity. While ***EMG + MT*** showed improved system reliability, it still grappled with nuanced issues related to sensor responsiveness. Overall, conditions ***C*** and ***EMG + MT*** experienced broader technical difficulties that hindered performance. The absence of significant difficulties in ***C + EMG*** and ***C + MT*** suggests these conditions were more stable, but recurring issues in ***C*** and ***EMG + MT*** underline the need for refinements in system stability and EMG sensor responsiveness to create a smoother user experience.

Exemplifying: In terms of exemplifying and drawing parallels to daily tasks, the experiences in different conditions varied. In ***C***, users related the experience to familiar activities such as writing or everyday tasks that involve single-handed operation. One user noted, "Yes, I can do that when I'm writing my master's thesis." In ***EMG + MT***, users made a more specific comparison to complex activities that require independent hand movements. One participant likened the experience to "one hand making a movement or having a rhythm and the other hand in an entirely different rhythm," drawing a parallel to playing drums, where each hand operates separately but in coordination. This analogy helped explain the novelty of performing distinct tasks with each arm, which felt unusual yet familiar in terms of multitasking. For ***C + EMG and C + MT***, no explicit comparisons to everyday tasks were mentioned. The lack of relatable examples in these conditions suggests that users may have found the actions less intuitive or less aligned with routine tasks in their daily lives.

Visualization of the Secondary Hand: The visualization of the hand significantly impacted users' experiences, with feedback highlighting the need for intuitive and immersive representations that align with the physical and virtual interaction. Many users expressed dissatisfaction when the visualization felt disconnected from their actual movements. For instance, one user noted that the controller felt as though it was "floating and not connected to my hand," which caused discomfort and a lack of embodiment. This disconnect between the visual feedback and physical control was a recurring issue, with users proposing that the representation should feel more integrated with their movements. Additionally, there was a preference for a contextualized visualization based on the theme or setting of the virtual experience. Some users mentioned that in specific environments, such as fantasy games, using a wand or lightsaber would make more sense, while in other scenarios, a more realistic representation of the hand might be preferable. One participant explained, "If we are in a fantasy world. . . a magic wand or a lightsaber would make sense." This indicates that users value the flexibility of the visualization being adapted to the context of the task or game, enhancing immersion.

11.5 General Discussion and Future Work

Regarding the used technologies, we found that EMG signal strength can differ more than we expected from the development phase. Even though we chose a very low amplitude value as a threshold, some participants had a harder time than others reaching that value, resulting in different effort needed to use that input mechanism, probably biasing the results. Furthermore, some people need longer than others to figure out how to contract the biceps without any body movement. In future studies, it would be interesting to see whether people prefer to decide which muscle to attach the EMG sensor to on their own. In general, EMG sensors need to be integrated in a more user-friendly way to be useful for a larger audience.

For motion tracking, on the other hand, we did not experience such problems. Having the movement of the arm directly mapped into the virtual world seems to be an easy and promising concept to further explore. While we used a cost-intensive external camera rig, tracking the hands is already possible for many up-to-date HMDs and should be extended by the manufacturer to support a broader variety of upper limbs.

We developed two interaction techniques that only featured one mechanic (either selecting or confirming). While the EMG-based one for pointing in many measures did not perform as well as other conditions, probably because of implementation issues, the motion tracking-based one for selecting performed significantly better than EMG only. This suggests that providing a controller with only limited functionality, and thus having to complete a task with both sides, is a promising concept. Hardware and software developers should strive for more flexible input designs that offer different levels of responsibility for each hand. Even with conventional input methods like controllers and hand tracking, solutions could be realized that offer only selecting responsibility for the secondary hand, while the primary hand takes on more responsibility.

With the input mechanic of both selecting and confirming for the secondary hand, people tended to enjoy that condition, even though it included the relatively hard-to-use EMG system. This confirms the findings on the user preference for bimanual tasks over unimanual tasks [255].

The findings from the second user study highlight the critical role of adaptive interaction techniques in enhancing the usability and accessibility of VR environments for individuals with upper limb differences. While participants initially faced a steep learning curve, particularly in conditions utilizing EMG sensors, usability improved with practice, indicating that familiarity with the system can mitigate some early challenges. The dual-hand tasks introduced cognitive engagement, which was generally appreciated by participants; however, muscle tension and coordination difficulties remained significant barriers to sustained use. Ergonomic considerations emerged as a key area for improvement. Participants suggested that more natural hand positioning, along with fine-tuned input thresholds, could reduce physical strain and enhance overall comfort. Additionally, system stability played a major role in user experience. Technical difficulties, such as lagging and misalignment, disrupted task flow and contributed to user frustration, emphasizing the need for more reliable performance in future iterations. Another important factor was the visualization of the secondary hand. Participants expressed a preference for visual feedback that felt intuitive and connected to their movements. Suggestions included context-sensitive visual representations, such as using a magic wand in fantasy environments, which would increase immersion and provide a more engaging experience. Regarding task load, we found that ***EMG + MT*** reduces effort and frustration while maintaining high physical and temporal demands, offering a balanced workload despite higher costs in certain areas, compared to the unimanual condition. We found that the interaction techniques were received well not only by users with upper limb differences, but also by a broader audience, showing the value of universal design.

Taken together, we suggest that VR systems should be designed in a more inclusive way, not only to enable all users to use them but also because everyone could benefit from novel input modalities and various input techniques to choose from.

11.6 Conclusion

In this work, we developed three alternative VR input techniques in a user-centered design process and evaluated them in two user studies. To answer research question **RQ2.2.1**, user satisfaction with bimanual interaction techniques was similar or less compared to unimanual interaction. Both conditions that include EMG performed worse in terms of usability than the baseline condition with the controller only, suggesting more familiarization time is needed to use that technology easily. However, the bimanual interaction technique with motion tracking only was not statistically different from the usability of the baseline condition, suggesting two things: First, motion tracking is an intuitive input mechanic that can be easily used. Second, having only limited responsibility of the secondary hand (selecting only) does not limit the user experience. Regarding efficiency, all conditions were on a similar level, except for one, where we assume this is due to the design issue of the VE. Both the condition with motion tracking only and the one with EMG and motion tracking were not statistically significant compared to the baseline condition. This means that even if EMG was harder to use, the user was still equally successful in completing the task at the same time. This highlights the importance of bimanual interaction in terms of efficiency. To answer research question **RQ2.2.2**, users with upper limb differences enjoyed performing tasks with different arms, showing the importance not only of software-based accessibility solutions like uni-manual input modes, but also the users' desire to use their secondary hand in VR.

In this chapter we explored the use of EMG as an alternative input method for HMDs, in combination with either a conventional motion controller or visual motion tracking. We found, that despite some technical difficulties, many participants were able to use EMG only after a short familiarization time. So in the next chapter, we further explore how EMG can be used to support another rising input technology in HMDs, eye gaze input, which is similar to motion tracking of the arm in terms of input paradigm (pointing). In the following, we present a two-part user study evaluating EMG sensor placements on different body parts and the Usability of the according gesture for confirming eye gaze selection.

12

EMG-based Confirmation of Gaze Selection Using Body Gestures

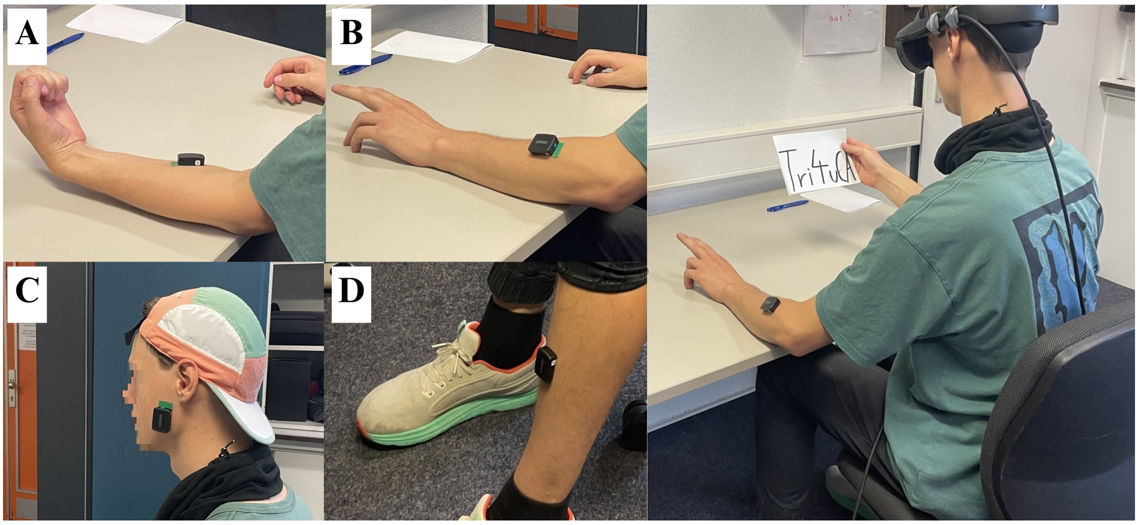


Figure 12.1: EMG-based confirmation of eye gaze selection: (left) Evaluation of optimal electrode placement on (A) the inner forearm with palm lifting as selection confirmation, (B) the outer forearm with finger tapping, (C) the jaw with biting, and (D) the shin with foot tapping as selection confirmation, respectively. (right) A participant enters a password with eye-tracking and EMG-based finger tapping.

This work explores EMG electrode placement on legs, arms, and the face and compares four gestures for confirming gaze selection in terms of usability. We then conducted a user study assessing EMG-based confirmations with the two most referred gestures versus a hand gesture method (pinching), using built-in hand tracking. This chapter investigates **RQ 2.3** and is based on the following publication:

- J. Hartfill, M. Arz, and F. Steinicke. "EMG-based Confirmation of Gaze Selection in Extended Reality". In: *Proceedings of the Mensch Und Computer 2025*. MuC '25. New York, NY, USA: Association for Computing Machinery, 2025, 375–384. ISBN: 9798400715822. DOI: 10.1145/3743049.3743062. URL: https://doi.org/10.1145/3743049.3743062

12.1 Introduction

EMG offers the possibility to be used at different muscles among the body, for muscles that are close to the skin and can be consciously tensed. This makes EMG a flexible input mechanic, being attachable to different body parts, depending on personal preference or physical condition, or depending on the used application. Muscles can be flexed without any body movement, allowing the extremities to rest comfortably on a table or in the lap when sitting and allowing the user to interact in physically limited spaces such as aircraft cabins. The sensors can be covered with cloths, making the interaction invisible, which might be interesting when using this technique in public spaces.

EMG has been explored as an alternative input mechanism for human-computer interaction, particularly through the use of facial EMG combined with gaze selection, which has been researched in the context of 2D screen input [5, 142, 176, 222, 249]. Pai et al. [196] evaluated an EMG confirmation method for selection with gaze in VR, with the EMG sensor being attached to the user's forearm. They found EMG confirmation to have a higher throughput than selecting with dwell time.

Building upon these findings, in this work, we further investigate the potential of EMG for gaze input confirmation in VR. In the first part of this work, we present a pilot study with 8 participants to investigate research question (RQ) 1: What muscles/positions of the electrodes are suitable for confirming gaze selection? We evaluated user preference and task completion time for four different EMG sensor placements on the body (forearm extensor, forearm flexor, masticatory muscle, and tibialis anterior/shin).

We identified the two best-performing positionings (forearm flexor and tibialis anterior/shin) and compared them in a larger-scale user study to a camera-based gesture confirmation approach [202] via hand tracking, similar to the one used in the Apple Vision Pro. We recruited 26 participants to evaluate task completion time and error rate, as well as user experience and task load, to answer RQ2: How does EMG confirmation perform compared to hand tracking-based confirmation of eye gaze input? In both studies, selection was done using eye gaze, with a visual feedback ("highlighting") of the selected item on the graphical user interface (GUI), and confirmation of the selection was done either with EMG or, in the main user study in the baseline condition, with a camera-based gesture.

This work is structured as follows: Section 12.2 provides a context of research that has already been done in this field, and the technical setup is described in Section 12.3. The pilot study is presented and discussed in Section 12.4 and the main user study in Section 12.5. Conclusions and limitations will be presented in Section 12.6 and Section 12.7.

12.2 Related Work on Confirmation Techniques for Gaze Selection

Gaze-based interaction has been investigated in the field of human-computer interaction for some time. It was first explored in 1990 by Robert Jacob [124], who used an eye tracker in combination with a screen and identified the potential of this interaction method and identified the Midas touch problem of gaze-based interaction.

EMG has been widely researched for selecting in 2D setups with facial EMG sensors, showing mixed findings. Surakka et al. [249] evaluated frowning as a confirmation technique for gaze input against mouse input. Participants performed a point-and-select task on a computer screen with either a mouse or gaze and frowning. Results indicated that the mouse was significantly faster than gaze and EMG for short distances between the start and target object (60 mm) but not for middle and long distances (120 and 180 mm). The authors hypothesize that the new techniques were slower because the used gaze tracker needed time to correctly measure the users' gaze. However, throughput was higher for gazing and frowning, and participants perceived the novel method to be faster. In a similar setup, San Agustin et al. [5] evaluated facial EMG confirmation against mouse button clicking for gaze input. In a Fitt's Law [169] task, they found throughput and completion time not significantly different between both confirmation methods, but the mean error rate was higher for EMG confirmation compared to mouse button clicking.

San Agustin et al. [222] also developed a low-cost setup for gaze selection and facial EMG confirmation and evaluated it in a mobile and a stationary setup against mouse input. For the mobile setup, they found EMG confirmation to be faster than mouse button confirmation for gaze selection. No difference between throughput and error rate could be found. In the stationary desktop scenario, no effect of confirmation method on completion time was found, but throughput was higher for mouse confirmation than for EMG confirmation, and error rate was higher for EMG confirmation than for mouse confirmation. Kocejko et al. [142] evaluated EMG confirmation against a dwell time approach for gaze input confirmation of a smart glass application. While they found 100 ms of dwell time giving satisfying results in their setup, for EMG confirmation, the average selection time was 890 ms. The shortest registered time for EMG was only 440 ms.

In the context of VR, Pai et al. [196] proposed a method based on EMG to confirm selection with gaze. They analyzed the throughput of different confirmation methods and found that EMG had a significantly higher throughput than confirming with dwell time.

In this work, we first investigate optimal electrode placement for EMG confirmation in VR. For facial placement, we chose to use the jaw muscle (masseter muscle), as it does not interfere with the HMD placement. For forearm placement, we investigated forearm extensor and forearm flexor. Additionally, electrode placement on the chin (Tibialis anterior) was investigated. In the second part of this work, we compare EMG-based confirmation with gesture confirmation via built-in hand tracking.

12.3 Setup

The EMG signal was acquired using the Delsys Trigno Lite System[1] together with the Trigno Avanti Sensor[2]. The sensors were set to a mode that outputs rectified EMG data (EMG RMS, 148 sa/s RMS Update rate, 100 ms RMS window, 20-450 Hz EMG bandwidth). The participants attached the sensor to their upper arm on their secondary side in the area of the biceps with medical tape. They were then instructed to tighten the biceps without moving the arm. For classification purposes, we utilized a threshold technique. During preliminary tests, we observed the resting potential to be below 0.05 mV. Even slight contractions of the biceps usually exceeded 0.01 mV. So we set the threshold to 0.03 mV, which was easy to activate while balancing false-positive classification. During both studies, participants could practice activating the threshold and fine-tune it if necessary until they felt comfortable. The data was transferred via Bluetooth to the Trigno Lite System, which is connected via USB to the PC, running the necessary software. The data was live-streamed into Unity via the API.

12.4 Pilot Study

We conducted a pilot study to investigate user preference and task completion time for four different electrode placements over the body. The muscle groups were tested in connection with specific gestures. This approach aimed to reduce cognitive load for users. Gestures might be less difficult for users to understand and perform when compared to instructions to consciously activate one specific muscle. Muscles had to meet two criteria: Firstly, they needed to produce a strong EMG signal. For that, they had to be close to the skin. Second, users had to be able to control these muscles effectively, achieved by selecting appropriate gestures. The chosen gestures and their corresponding muscles were lifting the palm inward toward the forearm (flexors of the forearm), tapping multiple fingers on a surface (extensors of the forearm), lightly biting down (masseter muscle), and tapping of the foot (tibialis anterior), see Figure 12.1.

12.4.1 Measures

In a within-subjects design, we evaluate the four different electrode positionings in terms of task completion time and user preference, using a short questionnaire with three items and three control items; see Table 12.1. Participants answered on a five-point Likert scale from "I fully agree" to "I completely disagree." The questions appeared in random order for each condition.

After completing all four conditions, participants answered open questions and were asked to do a ranking between the conditions. Additionally, task completion time was collected. The pilot study aimed to identify potential complications and challenges,

[1] https://delsys.com/trigno-lite/

[2] https://delsys.com/trigno-avanti/

Table 12.1: Questionnaire items for the pre-study (English translation).

Q1	I could utilize this muscle activation over an extended period of time
Q1C	I could only use this system for a short period of time.
Q2	The activation of the muscle was not disruptive and was not exerting.
Q2C	Using the EMG system was exhausting and disruptive.
Q3	I felt strange during the activation of the muscle.
Q3C	Using the system felt completely normal.

thereby facilitating their mitigation in the subsequent main study. Participants were recruited via the internal university recruitment platform and received study credit for their participation. Exclusion criteria included wearing large glasses that would not fit inside the VR HMD, having any severe neurological conditions that could interfere with EMG readings, and lacking fluency in German, as the study was conducted in German.

12.4.2 Materials and Implementation

For the pilot study, a simple VR selection task was developed in Unity[3] for the Meta Quest 2[4]. To read EMG signals, the Delsys Trigno Lite system[5] with a Trigno Avanti sensor[6] was used. The sensor is equipped with four dry surface electrodes. We used the rectified EMG data mode. A Windows 10 PC with 32 GB RAM, an NVIDIA GeForce RTX 4080 graphics card, and an Intel® Core™ i7-14700KF CPU was used for the study.

For the EMG to function as a confirmation method, a threshold for the activation had to be set. For this, Otsu's [195] method was used: The method calculates a single threshold based upon maximizing inter-class variance. The gesture's completion was synchronized with the selection using this threshold. Specifically, the signal needed to exceed the threshold and then fall below it again to mark the point of activation. The calibration of the EMG threshold was done by running the Unity project for about 20 seconds; the participants were asked to do the gesture several times and have the muscle relaxed meanwhile.

The Unity implementation looked as follows: Before the core task started, users could perform a simple test to get a feel for the interaction method. They had to move their head so a small reticle overlapped the object (head gaze input). For this, the Quest 2's head-tracking was used. To activate the confirmation, they then had to perform the EMG gesture. Objects were either "active" or "inactive." This was indicated by the color of the object and also trained in the testing phase (see Figure 12.2). Upon selecting the "active" object, users were informed that the confirmation worked. When they selected the "inactive" objective, they were informed that the object was not selectable. In the main task, the confirmation worked the same; it simulated a simplified and abbreviated

[3] https://unity.com/
[4] https://www.meta.com/quest/
[5] https://delsys.com/trigno-lite/
[6] https://delsys.com/trigno-avanti/

Fitt's Law task [72]: In front of the participants, a virtual orb appeared in one of five possible locations and changed color after a short delay. As with the testing phase, with the color change, the object became "active," and task completion time to EMG-activated confirmation was measured. This was done so users had time to adjust their head gaze to the new object and could focus on reacting with the EMG gesture.

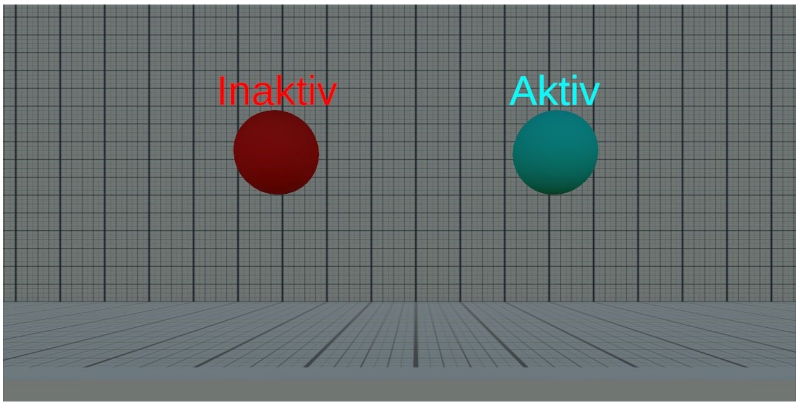


Figure 12.2: Participant view in the familiarization phase.

12.4.3 Procedure

Before the study, each participant signed a consent form and filled out a demographic questionnaire. After this, an EMG sensor was attached to the first muscle group via medical tape, and the users put on the HMD. The order of the four conditions was randomized. In each condition, participants performed thirty trials. Afterward, they were asked to answer how much they agreed with six different sentences about the EMG gesture regarding awkwardness, usability, and annoyance (see Table 12.1). After completing all conditions, participants were asked to respond to two open questions ("Which of the gestures and associated muscle activations did you find best + brief explanation?" and "Which of the gestures and associated muscle activations did you like the least + brief explanation?") and rank the different gestures based on their perceived daily usability.

12.4.4 Results

A total of eight students participated in the pre-study, consisting of five females and three males. Six participants were aged between 18 and 24, while two were between 25 and 34. Three participants had very limited experience with VR ("usage less than once per year"), while the remaining five were at least somewhat familiar with VR ("at least once per quarter year").

12.4.4.1 Task Completion Time

To analyze the task completion time for each electrode placement, we conducted a Friedman test, since the low number of participants did not allow for the assumption of a normal distribution. The differences (see Table 12.2) were statistically not significant according to a Friedman test (X^2 (3, N = 8) = 1.95, p = 0.58, n.s.).

Table 12.2: Median task completion times in seconds and interquartile ranges (IQR) for gestures.

Gesture	Task completion time (Median)	IQR
Foot tapping	1.46	0.69
Palm lifting	1.6	0.86
Finger tapping	1.63	0.68
Biting	1.58	0.47

12.4.4.2 Questionnaire

To evaluate the questionnaire, the confirming and denying statements were averaged, and then tests were performed to determine whether there was a significant difference between them.

Regarding usability, the median score for Finger tapping was 2.75 (IQR = 2.5), for palm lifting it was 2.5 (IQR = 2), for Finger tapping it was 1.75 (IQR = 1.12), and for biting it was 2.75 (IQR = 0.75). These differences were statistically not significant according to a Friedman test (X^2 (3, N = 8) = 4.72, p = 0.19, n.s.).

For the Likert scale regarding the annoyance, the median score for the Foot tapping was 2 (IQR = 1), for the Palm lifting it was 3.5 (IQR = 0.75), for Finger tapping it was 1.5 (IQR = 0.75), and for the Biting it was 2.75 (IQR = 1). A Friedman test indicated a statistically significant difference among the gestures (X^2 (3, N = 8) = 8.54, p = 0.0362). Six post-hoc Wilcoxon signed-rank tests, corrected with Holm's sequential Bonferroni procedure, were conducted to compare the gestures. The comparisons showed that none of the differences between the gestures were significant (see Table 12.3)

Table 12.3: Post-hoc comparisons between gestures show no significant differences in annoyance.

Gesture 1	Gesture 2	Wilcoxon signed-rank Test
Foot tapping	Palm lifting	V = 1, p = 0.62, n.s.
Foot tapping	Finger tapping	V = 23, p = 0.89, n.s.
Foot tapping	Biting	V = 8, p = 1.00, n.s.
Palm lifting	Finger tapping	V = 27, p = 0.20, n.s.
Palm lifting	Biting	V = 19, p = 1.00, n.s.
Finger tapping	Biting	V = 0, p = 0.13, n.s.

Regarding awkwardness, the median of the Foot tapping was 3.25 (IQR = 0.75), of the Palm lifting was 2.75 (IQR = 1.25), of Finger tapping was 4.25 (IQR = 1.12), and of the Biting was 2.25 (IQR = 0.625). These differences were statistically significant according to a Friedman test (X^2 (3, N = 8) = 14.2, p = 0.0027). Six post-hoc Wilcoxon signed-rank tests, corrected with Holm's sequential Bonferroni procedure, were conducted to compare the gestures. The comparisons indicated that none of the differences were statistically significant after correction (see Table 12.4).

Table 12.4: Post-hoc comparisons between gestures show no significant differences in awkwardness.

Gesture 1	Gesture 2	Wilcoxon signed-rank Test
Foot tapping	Palm lifting	V = 23, p = 0.89, n.s.
Foot tapping	Finger tapping	V = 0, p = 0.13, n.s.
Foot tapping	Biting	V = 25, p = 0.45, n.s.
Palm lifting	Finger tapping	V = 0, p = 0.13, n.s.
Palm lifting	Biting	V = 23.5, p = 1.00, n.s.
Finger tapping	Biting	V = 36, p = 0.09, n.s.

In the evaluation of the open-ended questions, Finger tapping was consistently favored, with seven out of eight participants describing it as intuitive and familiar to using a mouse. The Foot tapping followed, being ranked second by 6 out of 8 participants. In contrast, the Biting and the Palm lifting were consistently the least favorable, with five participants selecting "biting" and three selecting "raising the palm inward" as the least preferred. The Palm lifting was criticized for feeling awkward and unnatural, with some participants noting that it looked strange from an external perspective. Meanwhile, the Biting was described as physically tiring.

12.4.5 Discussion

Neither task completion time nor questionnaire results revealed significant differences between the four tested gestures, showing that the tested gestures with different body parts were equally well understood and practicable. This highlights the possibility of EMG to be used with different muscles or gestures without much training, even for more uncommon gestures like Palm lifting and Biting.

However, regarding user preference, there was a clear preference for Finger tapping or Foot tapping gestures over Palm lifting and Biting, showing that more common gestures are more easily accepted. Combined with such a simple threshold approach to detect the gesture onset, it would also be possible to let the user decide not only on the electrode placement but also on the performed gesture, just based on personal preference.

We noticed that the threshold method required manual adjustment for all participants, as the differences in EMG signal strength between users and muscles were larger than we had expected. So for the main study, we decided to use a different approach to detect the gestures.

For the main study, we decided to include finger and Foot tapping to evaluate those in an application task compared to a gesture-based confirmation method based on built-in hand tracking.

12.5 Main User Study

The pilot study provided valuable insights on EMG-based confirmation methods for gaze selection. Building upon this feedback, in the main user study, we focus on the Finger- and Foot tapping gestures and compare them against a standard pinching gesture with the built-in hand-tracking technology of the HMD. Such pinching gestures are common in up-to-date HMD for confirmation not only for eye tracking, i.e., in the Apple Vision Pro, but also for hand-tracking-based selection, as in the Meta Quest 2, 3, and Pro. We chose camera-based Pinching as the baseline condition, as it most closely resembles the suggested EMG-based confirmation techniques in terms of physical requirements and user experience, as it could be possible for the users not to think about the underlying sensing technology. Another well-established approach, dwell time, was not considered a meaningful baseline condition, as it would not directly allow for a comparison in task execution time due to the fixed time per confirmation. While in the pilot study the Meta Quest 2 was used in a VR setup, in the main study, we used the Meta Quest Pro, enabling gaze instead of head gaze, and investigated a more realistic augmented reality scenario with pass-through vision.

12.5.1 Materials and Implementation

The application was designed to simulate a simple XR user interface, where participants navigated through a menu system. The interface included a homepage with two pages, each containing seven applications. Among these, only the “Wi-Fi settings” application was functional. Upon selecting this app, participants could view a list of available networks and choose the correct one. Then a password input field appeared along with a virtual keyboard (see Figure 12.3). Participants had to enter the correct password to complete the task. If the password was incorrect, they were redirected back to the password prompt. Selection was based on gaze direction so that the item dwelled on was highlighted. Confirmation was done with either EMG or camera-based gesture, depending on the condition. The application was developed in Unity 2022.3.11f1 using the Nova UI package [7] and ran on a Windows 10 Laptop with 16 GB RAM, an NVIDIA GeForce RTX 2080 graphics card, and an Intel® Core™ i9-9980HK CPU.

In the pre-study, we experienced relatively long calibration times for the chosen classification algorithm. So to accelerate the calibration process, a different EMG gesture classification algorithm was used. Initial testing showed that similar results could be achieved with a simpler threshold approach: Participants were asked to relax the muscle for 30 seconds. The threshold was calculated from this data from the sum of the maximum value reached during the relaxation phase and one standard deviation. This approach was simpler and faster than the calibration process used in the pre-study, while achieving similar accuracy in detecting the gesture onset.

[7] https://novaui.io/

Figure 12.3: User study interface. Menu (top left), the Network Settings Page (top right), and Password Prompt (bottom).

12.5.2 Measures

We used a within-subjects design to evaluate the three confirmation modes (EMG finger, EMG foot, and Pinch), in terms of task completion time, error rate, task load, and user experience. An error was defined as entering an incorrect key, whether it was a letter, number, or symbol. To assess user experience, participants completed the short version of the User Experience Questionnaire (UEQ-S) [227] after each condition. Similarly, the NASA Task Load Index (NASA TLX) [103] was used to measure cognitive load for each condition, and the Simulator Sickness Questionnaire (SSQ) [215] was administered to evaluate simulator-related discomfort once before the experiment started and then after every condition.

Additionally, participants were asked to respond to two open-ended questions: ”What did you like about the input method?” and ”What did you not like about the input method?” These questions aimed to uncover insights for potential improvements in future research involving similar input technologies and to gather general opinions on the methods used. Finally, after completing all conditions, participants were asked to rank the input methods based on their perceived everyday usability and provide a brief explanation for their rankings, similar to the approach used in the pilot study.

12.5.3 Participants

A total of 26 people participated in the study. Participants could receive study credits for their participation. Exclusion criteria were the same as in the pilot study (see Section 12.4) with the addition that they weren’t allowed to already have partaken in the pilot study. The participants were on average 28.6 years old and ranged from 21 to 56 years. 15 were female and 11 male. They were additionally asked how they would rate their own VR experience on a scale from 1 (“No Experience”) to 10 (“Using VR Daily”). The average was 4.62 (SD = 2.28).

12.5.4 Procedure

Once participants entered the room and were ready, they were seated in front of a laptop, where they remained seated throughout the conduction of the study. First, they filled out and signed the consent form for participating in the study. They were also informed about the opportunity to voluntarily participate in an additional, integrated study. Participation in this optional study required signing an additional consent form and did not affect the main study.

After reading and signing the forms, participants completed the demographic section and the first SSQ iteration in the questionnaire. They were then briefed about the experimental conditions and that they would interact with the XR menu and enter the correct password. They were informed that the time taken to complete the task would be measured, but they were encouraged to perform the task at a "natural and comfortable pace.”

Four of the six condition permutations were completed by 4 participants each, while two were completed by 5 participants each. Depending on the starting condition, the EMG sensor was attached to their skin with medical tape, and participants were asked to put on the HMD and adjust it to their comfort. Once they were satisfied with the HMD’s position, they were instructed to calibrate the eye-tracking system, which had to be done outside the application.

Following the eye-tracking calibration, the Quest Pro was connected to the laptop via a USB cable, and the application was launched. If the current condition involved EMG-based interaction, a calibration was performed as described in Section 12.4. In each condition, participants were then provided the opportunity to familiarize themselves with the interaction method by practicing actions like opening applications, switching toggles, and using the virtual keyboard in text fields with eye gaze and the current confirmation gesture. The experimenter guided them through this process and asked if they felt ready to begin the main task.

During the task, participants were provided with a piece of paper containing the network password. After successfully entering the password and completing the task, they removed the HMD and proceeded to fill out the questionnaire. This procedure was repeated for all three conditions, with a different password for each to prevent a learning effect. The assignment of passwords to conditions was randomized to avoid interactions between the password and the input method. The passwords were created randomly, each containing lower- and upper-case letters and digits.

12.5.5 Results

12.5.5.1 Task Completion Time

The time taken to enter the password was compared across the three gesture conditions. The median time taken to enter the password for each condition was as follows: the Pinch condition had a median time of 50.2 s (IQR = 20.0), the Foot Tapping condition had a median time of 66.0 s (IQR = 67.7), and the Finger Tapping condition had a median time of 82.9 s (IQR = 90.6). According to a Friedman test, these differences were significantly different(X^2 (2, N = 26) = 13.5, p = 0.001).

Post-hoc Wilcoxon signed-rank test with a Bonferroni correction revealed a significant difference between Pinch and the Finger Tapping (V = 70.0, p = 0.018), with pinching outperforming Finger Tapping. No significant difference was found between the Foot Tapping and Finger Tapping (V = 234, p = 0.14, n.s.) and between the Foot Tapping and Pinch (V = 101, p = 0.06, n.s.).

12.5.5.2 Errors

To compare the rate of errors between the conditions, a Friedman test was conducted. The median error rates were 1 (IQR = 7.25) for the Pinch condition, 3.5 (IQR = 9.75) for the Foot Tapping condition, and 4.5 (IQR = 12.8) for the Finger Tapping condition. This difference between the conditions was not significant according to the Friedman test (X^2 (2, N = 26) = 5.89, p = 0.053, n.s.).

12.5.5.3 Simulator Sickness Questionnaire (SSQ)

The median of the SSQ score before the experiment was 7.48 (IQR = 24.3), after the Pinch condition, it was 9.35 (IQR = 19.6), after the Foot Tapping condition, 9.35 (IQR = 29.0), and after the Finger Tapping condition, 7.48 (IQR = 23.4). These differences were not statistically significant according to a Friedman test (X^2 (3, N = 26) = 1.0588, p = 0.787, n.s.).

12.5.5.4 NASA Task Load Index (NASA TLX)

Each dimension of the NASA TLX was evaluated with a Friedman test, comparing the different gestures. None of the differences were significant (see Table 12.5).

12.5.5.5 User Experience Questionnaire (UEQ-S)

The results for the UEQ-S can be seen in 12.4. Friedman tests were conducted to assess differences across the three conditions for overall UEQ-S, pragmatic quality, and hedonic quality.

The results indicated no significant differences in the overall UEQ-S score (X^2 (2, N = 26) = 3.78, p = 0.15, n.s.), while significant differences were found in pragmatic quality (X^2 (2, N = 26) = 10.6, p = 0.005) and hedonic quality (X^2 (2, N = 26) = 14.9, p = 0.001). Following

Table 12.5: Median scores and IQR for different conditions across the NASA TLX dimensions, along with Friedman test results.

NASA TLX Dimension	Condition	Median	IQR	Friedman Test
Mental Demand	Pinch	20	15	X^2 (3, N = 26) = 2.15, p = 0.34
	Foot tapping	20	36.2	
	Finger tapping	17.5	42.5	
Physical Demand	Pinch	7.5	20	X^2 (3, N = 26) = 4.8, p = 0.09
	Foot tapping	15	15	
	Finger tapping	15	18.75	
Temporal Demand	Pinch	12.5	17.5	X^2 (3, N = 26) = 2.39, p = 0.30
	Foot tapping	15	25	
	Finger tapping	15	15	
Performance	Pinch	12.5	17.5	X^2 (3, N = 26) = 5.24, p = 0.07
	Foot tapping	15	20	
	Finger tapping	25	33.75	
Effort	Pinch	15	20	X^2 (3, N = 26) = 5.2, p = 0.07
	Foot tapping	25	36.25	
	Finger tapping	22.5	48.75	
Frustration	Pinch	15	20	X^2 (3, N = 26) = 5.26, p = 0.07
	Foot tapping	15	20	
	Finger tapping	17.5	43.75	

the significant Friedman test results for the pragmatic quality, Wilcoxon signed-rank tests were conducted with a Bonferroni correction. The analysis revealed significant differences between Pinch and Foot Tapping (V = 41.5, p = 0.006), with Pinch outperforming Foot Tapping. Pinch and Finger tapping (V = 45.5, p = 0.003) also revealed significant differences, with Pinch outperforming Finger tapping. No significant difference was observed between the Foot tapping and Finger tapping (V = 108.0, p = 1.00, n.s.).

Furthermore, post-hoc tests were conducted for the hedonic quality of the UEQ-S. The comparison revealed significant differences between the Foot tapping and Finger tapping (V = 17.5, p = 0.001) and Pinch and the Foot tapping (V = 248, p = 0.015). No significant difference was found between Pinch and Finger tapping (V = 160.0, p = 1.00, n.s.).

12.5.5.6 Open-ended Questions and Ranking

From the open-ended questions, themes were extracted and counted (see Tables 12.6, 12.7 and 12.8). Additionally, 7 participants mentioned the eye-tracking across all input methods to be a problem. 6 participants also noted that while typing, they felt the need to verify whether they had entered the correct letter, which led to changes in the selected letter on the keyboard due to a small delay between input and action. For both EMG-based conditions, 5 participants mentioned that they felt restricted in their freedom of movement due to not being able to move their arm/leg without triggering the EMG sensor. In the Finger tapping condition, 5 participants mentioned that they did not like that they had to

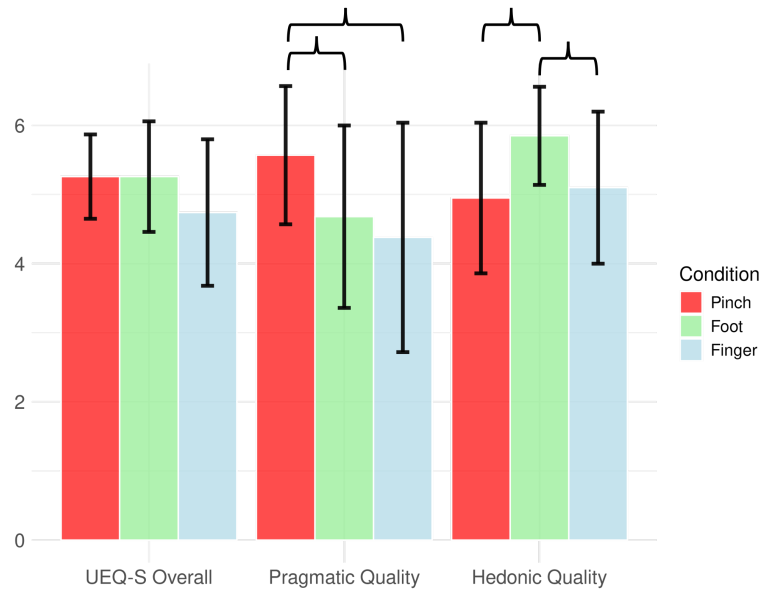


Figure 12.4: Results of the UEQ-S. Brackets mark significant effects ($p < 0.05$).

keep their hand relaxed when not selecting and instead kept their finger hovering.

As for the ranking in daily usability, Pinch was consistently favored, with its average ranking being 1.38. Both EMG-based input gestures were ranked the same, with an average ranking of 2.31.

Table 12.6: Quantification of Positive and Negative Themes for the Pinch Input Method.

Positives		Negatives	
Theme	Mentions	Theme	Mentions
Fast	7	Physical Strain	1
Intuitive	8	Mental Strain	3
Accurate	7	False Positives	3
Familiar	5	Unintuitive	2
Easy	5	Inaccurate	2

Table 12.7: Quantification of Positive and Negative Themes for Finger Tapping Input Method.

Positives		Negatives	
Theme	Mentions	Theme	Mentions
Fast	1	Physical Strain	2
Intuitive	7	Mental Strain	2
Accurate	1	False Positives	3
Familiar	2	Unintuitive	2
Easy	1	Inaccurate	5

Table 12.8: Quantification of Positive and Negative Themes for the Foot Tapping Input Method.

Positives		Negatives	
Theme	Mentions	Theme	Mentions
Fast	3	Physical Strain	1
Intuitive	3	Mental Strain	3
Accurate	3	False Positives	4
Familiar	0	Unintuitive	1
Easy	5	Inaccurate	1

12.5.6 Discussion

Task completion time did show a significant effect, with Pinch being significantly faster than Finger tapping. However, Pinch was not significantly faster than Foot tapping. This might show a design flaw in the tipping gesture: Users had to relax their hand when not actively performing a confirmation. Many participants hovered their fingers, possibly due to prior experience using a computer mouse or trackpad. The hovering already produced an EMG signal, accidentally triggering the confirmation functionality. This shows the EMG input gestures should be carefully designed around other well-known gestures.

In error rate, no significant differences to the camera-based gesture could be found. However, although not significant, the EMG conditions did have a slightly higher error rate, suggesting that the gesture classification of the EMG system can be further improved. This finding supports that EMG-based input could be useful in scenarios where visible gestures are undesired or not possible due to social acceptance or space limitations.

Some participants reported the sensitivity of the EMG system being too high and thus producing false positives. Some also mentioned this for the pinching condition. The occurrence of false positives in both EMG and non-EMG conditions might be caused by a slight delay between selecting the key on the keyboard and the character appearing in the text field. Another factor for false positives could be the EMG calibration method, which produced a quite sensitive threshold, which could easily be triggered if the participants changed their arm or leg position during trials. When designing EMG gestures, the underlying detection algorithm should be considered. While our simple threshold approach was sensitive for false positive detection, a more fine-tuned approach might have allowed us to use more complex gestures or allow for more diverse execution of the gestures.

The results from the NASA TLX showed no significant differences for task load between the conditions in all dimensions. Contrarily, when asked directly, users reported the EMG input methods to be “less intuitive” and “straining” (both mentally and physically). However, the perceived task load was not higher for the EMG conditions. Effect sizes may have been too small to be found within this sample. With longer sessions or more participants, mental or physical strain might become more apparent. Nonetheless, not finding significant differences between the conditions in all NASA TLX dimensions indicates that the EMG-based input methods might be a suitable alternative method for confirmation for gaze input without increased workload.

Regarding the overall UEQ-S scores, no significant difference between the three conditions could be found. When looking at pragmatic quality, pinching scored significantly better than both EMG conditions. This corresponds with what users reported and shows the necessity to improve the calibration duration and quality in future studies.

In contrast, the score for hedonic quality was significantly higher for the Foot tapping condition than for both other conditions. The UEQ-S includes questions about novelty, such as "inventive" or "creative," which the EMG system might have scored exceptionally high in, While Finger tapping might also be inventive or creative, the technical restrictions and complications and also the fact that participants were unable to move their arm (apart from the tapping) could be reasons why its score was lower. Keeping the leg still may be more natural for most participants than not moving the arm. Some participants even explicitly mentioned that they felt restricted in their movement when in the Finger Tapping condition, whereas in the Foot Tapping condition, some said they liked having both hands free.

The ranking clearly showed that participants favored Pinch regarding daily usability. While technical difficulties, movement restrictions might hinder EMG-based confirmation to be as good as pinching, it also has to be said that pinching is simpler concerning required hardware. Having an extra EMG sensor requires more resources and makes it less cost-effective than camera-based gestures. Another contributing factor could also be familiarity. EMG was reported to be less familiar to most participants, and some directly mention its novelty, which is shown additionally in the UEQ-S results. Training and adaptation could have had an impact on the performance and the user experience and thus, indirectly, on the ranking. The EMG gestures were chosen to be simple, but as shown by the conflicting memory of how computer mice are used, more training and adaptation would possibly have helped. It would have also, however, reduced the novelty of the interaction and thus lowered the hedonic score. Moreover, the pinching gesture, independent of the underlying sensing technology, could have been more familiar to the participants, as participants reported having some experience with VR technology. However, we did not explicitly ask for experience with specific hand gestures. During the conduction of the study, participants could get familiar with each gesture, and we did not notice any difference between the familiarization phases of each gesture in terms of duration, nor did any gesture seem more difficult to get familiar with than the others.

Taken together, our findings suggest that EMG-based gesture detection can be a valuable option for gaze input, with error rate and task load not being significantly different from camera-based pinching. Broadening the range of possible input techniques helps to improve technology accessibility. EMG sensors can be easily applied and taken off and can be used according to one's own preferences and context. However, the calibration and gesture design need to be considered carefully.

12.6 Limitations and Future Work

The accuracy of the EMG calibration could be further improved. Choosing a machine learning approach might be more suitable to identify gestures better. In this work, also, just one singular EMG sensor was used. More sensors would enable a broader stream of EMG data and could, potentially, enhance classification.

Another factor that might be of interest in future research is the choice of muscles. In the pilot study of this work, Biting and lifting the palm inwards were not favored by the participants. However, the participants in both the pilot and the main study did not have physical limitations. Future studies should consider more diverse participants and explore more different gestures with different muscles.

Furthermore, exploring the use of EMG gestures in public spaces would be interesting to investigate how these findings relate to a similar setup, where the user is potentially watched by others.

12.7 Conclusion

This work has investigated an alternative, EMG-based method of confirmation in virtual and extended reality, integrating a single surface EMG sensor with simple threshold classification and the Meta Quest Pro's eye-tracking capabilities. Experimental results from the pre-study revealed that Finger- and Foot tapping were favored by participants.

Building on these findings, these two EMG-based input variants were compared to a camera-based Pinch gesture. While user evaluations favored Pinch overall, EMG-based input demonstrated comparable performance in task efficiency, user experience, and task load assessments.

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Conclusion

In Part III of this dissertation, we investigated how VR systems can be designed for the diverse human body, investigating **RQ2**. For that, we first investigated the effect of self-configured avatars on embodiment. Second, we developed novel forms of interaction with immersive VEs to enable both users with and without temporal or chronic conditions of the upper limbs to use such technology.

RQ2.1 What effect do truthfulness and self-representation have on embodiment? The aim of RQ2.1 was to investigate the role of avatar self-configuration on SoE. For that, we presented a study with 30 participants who experienced three levels of self-avatar visual fidelity: (i) A generic avatar that users could choose among 13 avatars, (ii) a self-configured avatar that did not necessarily match the users visual appearance, and (iii) a photo-generated avatar. All avatar types had the same anthropomorphism level and realism level, as they were generated using the same tool. The results of the embodiment questionnaire revealed no significant differences between the avatar types. However, indirect measures for embodiment (valence, arousal, and reaction to threat) were significantly higher in the self-configured avatar compared to the other two. This indicates that even if self-configuration does not directly affect SoE, it does alter the users' feelings towards their avatar, which might not be reflected in the questionnaire we used.

RQ2.2 What role does the secondary hand have in VR? To answer RQ2.2, we investigated input techniques based on motion tracking and EMG data, based on a user-centered design process including participants with unilateral limb differences or fine motor issues. We found that input mechanics with limited responsibilities of the secondary arm can be equally efficient and usable as sequential task completion using only one controller. This is especially the case for motion tracking, which is an intuitive and established input mechanic for VEs. However, we could show that EMG can also be used without prior practice and lead to satisfying results, but results are limited due to technical difficulties regarding the setup. So, to answer RQ2.2: We found that users do not necessarily need the full functionality on both hands for a good user experience. However, splitting the input mechanics of one task so that both sides are involved seems to add some cognitive load and should only be used when necessary. Furthermore, novel sensor types like EMG should be further investigated, as they offer novel possibilities for interaction.

RQ2.3 How does EMG-based input compare to traditional pinch gestures in terms of task efficiency, user experience, and cognitive load in user interactions? Regarding RQ2.3, we investigated four different electrode placements on different body parts in a preliminary study. Results showed no difference in efficiency, but users expressed their preference for foot tapping and finger tapping, suggesting that more common gestures are preferred. These gestures were then evaluated against camera-based finger pinching gestures. In our results, pinching outperformed the EMG-based gestures. However, we expect with a longer familiarization time, the proposed gestures could be equally usable while being less dependent on the movement capabilities of the users' arms, hands, and fingers.

Part III of this thesis investigated how VR systems can be designed for the diverse human body in terms of virtual representation and input techniques.

Regarding the embodiment of a full-body motion-tracked avatar, we found that users perceive their virtual versions differently, depending on its appearace. When being embodied in a self-configured avatar that did not necessarily resemble the user's actual visual appearance, we found higher scores in indirect measures for embodiment than in the generic avatar condition. Interestingly, for the photo based avatar condition, such an effect could not be found. This shows the considerable potential of VR: Virtual worlds can diverge from the reality that we are familiar with, and researcher sand VR designers should explore more ways in which this diversion from the reality could be beneficial both for individuals and the society.

We also investigated novel interaction techniques for VR systems and found that input methods do not necessarily need to support the complete input functionality that is needed for the virtual experience but can also be limited, such as pointing only. We investigated a combination of motion tracking and EMG. While motion tracking is intuitive and known to most users, EMG is rather unknown and less intuitive to use. Still, users achieved similar task completion times, showing that it is worth investigating novel sensor technologies, as it broadens the input possibilities and thus can make VR accessible to more people. Similarly, while most up-to-date HMDs have tracking options for the head and upper limbs, other body parts are rather neglected for input. We explore the use of various body parts, finding that foot tapping performed similarly to finger tapping, although it is probably less common for most people. By designing more modular controller types for HMDs that can be operated with different body parts, even if they might only have a limited functionality, immersive VR systems could be much more accessible and comfortable for everyone.

Part IV

Conclusion

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Summarizing Conclusion

This thesis explored the question of how we want to interact within a virtual world in two ways: Firstly, we further investigated the basic concepts that elicit the feeling of embodying virtual hands by analyzing the effect of the visual appearance of the virtual hand, the sensitivity to redirections of the virtual hand, and the interplay of both of these factors. While we did find that redirection sensitivity differs between different motion directions, we could not find an effect of the appearance of a virtual hand on redirection sensitivity, suggesting that while motor synchrony affects SoE, SoE does not affect sensitivity to motion redirection. So when designing interaction techniques based on virtual hands, artists and programmers should consider the importance of both the visual appearance of virtual hands and the mapping between the real and virtual hand, as both factors can enhance or diminish the illusion and the SoE toward the virtual body in general. When changing the mapping between real and virtual hands, i.e., to redirect the users towards a target, to increase the virtual interaction space, or for promoting larger movements for medical reasons, designers of such interaction techniques should note that the amount of redirection that can stay unnoticed varies between all three spatial axes, as well as between the motion direction on each axis. Hence, if it is elementary that such manipulation stays unnoticed, redirection should only be applied as much as necessary. For the visual appearance of virtual hands, the degree of realism appears to be important for SoE, likewise its anthropomorphism, similar to findings for the whole body. Having the same physical structure as the real-world body part makes the multisensory integration easier and, thus, increases SoE. However, to the best of our knowledge, there are no consumer-level applications that provide apart from 5-fingered hand models, disregarding the variety of human bodies. A way to equip people with virtual models of their hands is by 3D scanning their hands and creating a fully articulated hand model for the VE. We provide practitioners with a fast and simple workflow based on free software solutions to create such models within 30 minutes (see Chapter 7).

VR has been criticized as an ableist technology [85]. Regarding interaction techniques, both controllers and hand tracking are designed for *able-bodied* people first and can pose problems for people with diverging body layout our motor problems of the hands and arms. In the second part we consider VR accessibility and representation in the context of body diversity. For that, first, we investigate the role of self-configured avatars for SoE as a means to further increase immersion in virtual worlds, as it offers the possibility to present ourselves independent of our actual visual appearance. We found evidence suggesting increased SoE for self-configured over photo-generated avatars, highlighting the need to further explore the possibilities VR offers, going beyond reality. Secondly, we developed novel interaction techniques for VR, with varying levels of responsibility for the secondary hand, based on EMG and motion tracking. Finally, we used our experience with EMG as an input device to explore body gestures as confirmation techniques for eye gaze selection, providing a flexible possibility independent of body schema or physical abilities. Regarding input techniques for bimanual tasks, we found that novel concepts with limited responsibility for the secondary hand can be equally efficient and usable as using a conventional unimanual mode. Our study on body gestures for gaze confirmation showed that such gestures can be similar in error rate, while task completion time was lower for a conventional pinching gesture. Taken together, these results indicate that people can quickly learn how to use such novel techniques, even if they never encountered them before, such as in the case of EMG. As many people would benefit from more diverse input techniques for XR devices, such as people with chronic or temporal conditions of the upper limbs, manufacturers of HMDs should not only explore more diverse input devices, but they should also open up their systems to include accessibility devices that are already established in other domains, such as PC usage. Even if such devices only have a limited capability, such as pointing only (i.e., a joystick) or confirming only (i.e., a button), they can be helpful in combination with other input devices.

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Outlook

To summarize, we explored interaction techniques based on hand input and body, with a special focus on SoE and the development of novel input techniques. Regarding SoE, we could confirm the importance of avatar visual fidelity and found that SoE increases with the morphological match between the virtual and the real hand. Also, the role of self-representation needs to be further explored, as our findings suggest increased SoE for a self-configured over a photo-based avatar. Especially the role of 3D-scanned avatars (not only photo-generated ones) on SoE remains an open question. Redirection sensitivity, however, seems to be independent of avatar appearance. While motor synchrony is known to be linked to SoA, and, thus, SoE, the effect does not seem to be bidirectional. However, whether these findings also apply to personalized photorealistic hands remains an open question. When investigating novel input techniques based on EMG, which most participants had never experienced before, most people could use the prototypes after a short familiarization phase, even if they used the EMG device on a body part that is usually not associated with VR interaction. While in our works we used simple approaches to classify the EMG signal, machine learning techniques allow for more complex interpretation of such signals. This would make it possible to use a single sensor position not only as a binary input device, like a button, but also a continuous interpretation would be possible. It would be conceivable to map signal strength to one of the spatial axes of an object, allowing it to move the object in one direction depending on muscle tension. Or using several gestures with distinguishable signal patterns, it would be possible to switch the operation mode of the EMG sensor, depending on the application.

Taken together, there are several possibilities to enhance HMDs in terms of software and hardware. Both users who use VR systems regularly and people who face problems with conventional VR setups could benefit from such improvements, like personalized or self-configured avatars or more diverse input techniques. While VR HMDs are already commercially available for several years, they are still more of a niche product for VR enthusiasts. Making the technology more easily accessible and more enjoyable for all could help change that role of VR to a more universally applicable device that could be better applicable in other contexts, such as for rehabilitation and psychotherapy.

Eidesstattliche Erklärung

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Hamburg, July 22, 2025

Judith Hartfill

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