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The Impact of Avatar Completeness on the Detectability of Hand Redirection in Virtual Reality

submitted by
Simon Seibert
Saarbrücken
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Advisors:
André Zenner, Martin Feick
Saarland University & German Research Center for Artificial Intelligence
Saarland Informatics Campus
Saarbrücken, Germany

Reviewers:
Prof. Dr. Antonio Krüger
German Research Center for Artificial Intelligence
Saarland Informatics Campus
Saarbrücken, Germany

Dr. Martin Schmitz
Human Computer Interaction Lab
Saarland Informatics Campus
Saarbrücken, Germany

Submitted:
May 12, 2023

Saarland University
Faculty MI – Mathematics and Computer Science
Department of Computer Science
Campus - Building E1.1
66123 Saarbrücken
Germany

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Abstract

Virtual reality (VR) allows users to be visually immersed in a virtual environment (VE) where real movements are usually mirrored in a one-to-one manner. The VR interaction technique called hand redirection (HR) breaks this one-to-one mapping by applying an offset to the user's virtual hand. This allows the user's physical hand movement to be redirected and thus manipulated to a certain degree. Doing so can greatly improve a VR experience through better utilization of limited space [35, 45], increased interaction speed or precision [9], and even a more authentic haptic experience [2]. Applying too much HR, however, will cause a person to notice the illusion, signifying that their hand redirection detection threshold (HRDT) has been surpassed. Previous studies have already shown that the appearance of the user's virtual body, i.e., the avatar, can influence these HRDTs greatly [33].

In this thesis, we explore how avatar appearance in VR, particularly its completeness, affects the sense of embodiment and subsequently the perception of HR. To this end, we conducted a psychophysical experiment with 20 volunteers, each of whom embodied four different avatars with varying degrees of completeness. In this, one avatar only visualized hands with an abstract appearance, a second avatar showed arms in addition to the hands, a third avatar had a complete but abstract-looking full-body, and a fourth avatar had a realistic-looking full-body with a female and a male variant. The goal of the experiment was to determine the sense of embodiment and the HRDT for each of these avatars and for each participant. Their task was to repeatedly reach for a distant point with their right index finger. To this movement, we applied horizontal HR with various magnitudes of redirection while participants had to assess whether or not their hand movement was being manipulated. Since we explained the nature of HR to all participants in detail and participants could concentrate on assessing the presence of HR without any distractions, we obtained very conservative results in our study. Thus, these results represent a worst-case scenario for unnoticed redirection, whereby real HRDTs are expected to be higher due to distractions and other factors.

Our findings show a tendency that the completeness of an avatar correlates with a greater sense of embodiment. This finding supports the current trend seen in commercial VR applications to gradually shift from using detached hands to complete virtual bodies with the goal of further increasing immersion. In contrast to our expectations, however, we could neither confirm nor reject that the completeness of an avatar influences the perception of HR, as no significant differences were found for HRDTs when using four types of avatars with varying degrees of completeness. The thesis concludes with a discussion of why the experiment likely failed to reveal potential effects. Moreover, we summarize important aspects to be considered in future experiments studying the impact of avatar completeness on the feeling of embodiment and the detectability of HR.

Keywords: Virtual reality, hand redirection, full-body avatar, avatar-completeness, embodiment, perceptual thresholds

List of Abbreviations

VR	Virtual Reality
VE	Virtual Environment
HRDT	Hand Redirection Detection Threshold
HMD	Head-Mounted Display
AR	Augmented Reality
CD	Control-Display
HR	Hand Redirection
BO	Body Ownership
RHI	Rubber-Hand Illusion
VHI	Virtual-Hand Illusion
IV	Independent Variable
DV	Dependent Variable
ACL	Avatar-Completeness Level
IK	Inverse Kinematics
2-IFC	Two-Interval Forced Choice
GPoE	General Perception of Embodiment
ANOVA	Analysis of Variance
SSQ	Simulation Sickness Questionnaire

Contents

Chapter 1
Introduction

1.1 Motivation

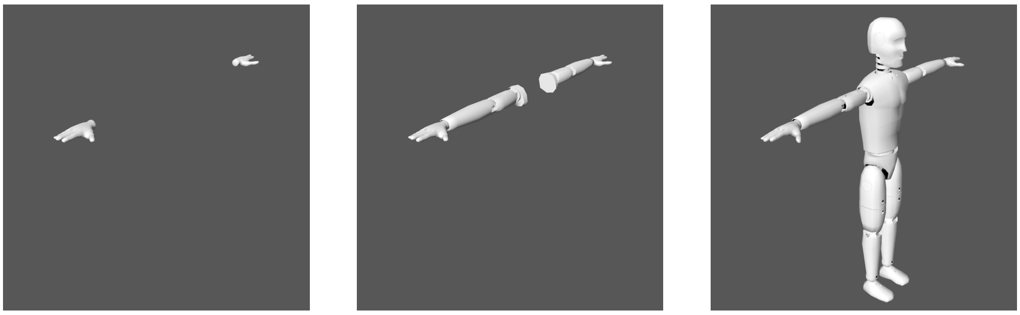
Virtual reality (VR) is an experience that allows users to enter virtual worlds realised through the use of computers. This is possible by deliberately manipulating the sensory impressions of a user in such a way that one perceives the virtual world as reality. As VR grows in popularity, advances in hardware and software are constantly being made, making immersion (i.e., the objective level of sensory fidelity a VR system provides [40]), stronger and stronger by more realistically manipulating one's senses.

However, there are still some technical challenges that make complete immersion not yet achievable. To give an example, it is still not possible to create a realistic depiction of haptic feedback. Controllers that do not differ from conventional video game controllers, except for the ability to be tracked in the environment are the current standard for manipulating virtual worlds. Therefore, such controllers only allow haptic feedback through vibration and the static haptic impression that is created by the act of holding the controller in the hand. Alternatively, one could replicate the virtual environment (VE) in real life and track every single object in it. In this scenario, no controller is needed, allowing the user to touch each object, resulting in a realistic haptic experience. This approach can work well for small explorable environments (e.g., a replica of an airplane cockpit), but it does not scale well. Recreating any given VE in its entirety is an unrealistic amount of work that would also make the use of a VR device obsolete.

To help solve this haptic problem, one can take a single instance of an object group from the VE, e.g., a single cup on a table with multiple cups, and recreate it in real life, so that it can serve to evoke haptic feedback by being able to touch and feel it (also called physical proxy [2]). Now the path of one's virtual hand can be modified in such a way, that the real hand will always end up at the physical cup, regardless of which of the multiple virtual cups the virtual hand is at, to provide a realistic sense of touch [2]. This powerful technique of diverging the path of the virtual hand from the real one is called hand redirection (HR). HR also enables users to extend their reach [35, 45], prevent the virtual hands from penetrating other virtual objects [33, 49], and more. However, HR can not be pushed as far as desired, because at some point users will notice that their virtual hands are not following their real ones. To maintain the illusion, the amount of redirection must remain within the so-called hand redirection detection threshold (HRDT) [47], otherwise the risk of breaking immersion is increased.

Looking at current trends, more and more VR applications are also visualizing a user's whole body[1] in the VE instead of just showing a pair of disconnected and floating hands[2], to create even higher immersion. Just recently, the world's largest provider of VR devices, Meta[3], added virtual arms and the upper torso to the previously detached virtual hands in the home screen. Meta is also experimenting with adding tracked legs and feet, bringing them closer to visualizing a user's entire body. These virtual depictions of oneself in VR are called avatars. Since for most VR applications, a user's immersion into a virtual world is the top priority, it is also important to give users a strong sense of embodiment towards their avatar (i.e., accepting the virtual avatar as your own body). This is very important as humans tend to be very body-oriented and, amongst other things, estimate the size of objects based on the appearance of their own bodies [32]. It was also found that the appearance of avatars can have a strong influence on the aforementioned HRDTs [33].

Consequently, the next logical step is to combine HR with full-body avatars. However, there is a lack of research regarding this topic, so it is not yet known how an avatar that visualizes and simulates the user's entire body would affect the sense of embodiment and HRDTs since so far VR research has not combined full-body avatars and HR. To our knowledge, there also seems to be no research on how the completeness of an avatar (see Figure 1.1), independent of its graphical realism, affects the sense of embodiment. For these reasons, we decided to conduct a study to investigate how the sense of embodiment and HRDTs are influenced by increasingly complete (i.e., 'full') avatars.



(a) Example of an avatar that only visualizes the user's hands.

(b) Example of an avatar that visualizes the user's arms in addition to the hands.

(c) Example of a full-body avatar.

Figure 1.1: Avatars with different levels of completeness.

[1] Commercial examples for full-body avatars:
https://www.oculus.com/horizon-worlds/
https://store.steampowered.com/app/1592190/BONELAB/

[2] Commercial examples for avatar that only visualizes hands:
https://store.steampowered.com/app/546560/HalfLife_Alyx/
https://www.playstation.com/en-us/games/horizon-call-of-the-mountain/

[3] https://www.meta.com/de/en/

1.2 Research Questions

The goal of this thesis is to explore the following research questions:

RQ1: What influence do more complete avatars, in terms of how much of the human body they depict and independent of their graphical realism, have on the sense of embodiment?

RQ2: Assuming RQ1 proves to be true, does the increased sense of embodiment affect HRDTs?

It is important to state the significance of these research questions. By formulating them in this way, we can determine whether the quantitative supplementation of body parts for avatars (i.e., adding limbs until the entire human body is depicted) is truly coupled with an increased sense of embodiment. When VR applications take the leap towards using full-body avatars, it is usually accompanied by a realistic-looking design in an effort to strengthen the sense of embodiment and the feeling of truly 'being' in the VE. Our first research question, however, allows us to explore whether more complete avatars in its pure sense, i.e., regardless of their graphical realism, provide a greater sense of embodiment.

With our second research question, which is our main research question of this thesis, we can also determine whether the trend of displaying more complete avatars also brings with it the possibility of being able to use HR more intensively without noticing it. As scientific papers [2, 8, 10, 22] have already shown the many possibilities offered by HR, such a finding would further reinforce its utility. On the other hand, it could also turn out that more complete avatars have a negative effect on HRDTs. Such a finding could then serve as a suggestion to use HR more carefully and with less intensity, such that a user does not notice its presence.

1.3 Research Approach

To answer these research questions, we will first define three different levels of avatar completeness in order to categorize different avatars. In line with the research questions, we will then conduct a user study involving HR where avatars from different levels of completeness are compared to each other. For determining HRDTs, we will use an adaptive method of psychophysics designed for measuring perceptual thresholds [13]. This method will be used to expose users to different levels of HR and inquire whether the stimulus was perceived to gradually approach the HRDTs. Using standardized questionnaires such as the 'Standardized Embodiment Questionnaire' developed by Franco and Peck et al. [15], the sense of embodiment will be determined for each level of avatar completeness. After the study has been conducted, the results will be analysed and the research questions can be answered.

1.4 Outline of the Thesis

In the following chapters, we will first have a look at existing research on the redirection of hands and the effects avatars have on a VR experience. Subsequently, we will lay out a concept for a study we conducted that examines our proposed research questions. Following this, we will describe the implementation and execution of our study in detail. The results of the experiment will then be presented and their significance discussed. Finally, we will discuss the limitations of our study and give an outlook on possible future work.

Chapter 2
Related Work

2.1 Virtual Reality

Virtual reality (VR) has its roots in 1968 when Ivan Sutherland [42] created the first head-mounted display (HMD) (Figure 2.1). This device constantly generated a two-dimensional image for each individual eye creating stereoscopic images that give the illusion of seeing a three-dimensional object. It even took head movement into account, allowing a user to look at and occupy the same space as a virtual wire-frame object.

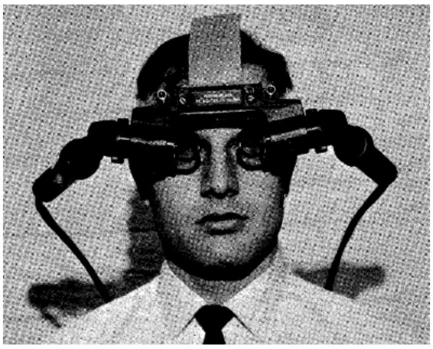


Figure 2.1: First HMD created by Ivan Sutherland [42] in 1968.

This concept was refined in the following years with the first consumer-friendly HMD called the Oculus Rift[4] being released in 2013. Today, anyone can explore virtual, computer-generated worlds with relatively cheap devices that sometimes do not even need an external computer and can run on their own like the Meta Quest 2[5] or Vive Focus 3[6]. Modern devices feature high-resolution screens, surround-sound audio and

[4]https://www.kickstarter.com/projects/1523379957/oculus-rift-step-into-the-game
[5]https://store.facebook.com/de/quest/products/quest-2/
[6]https://www.vive.com/us/product/vive-focus3/overview/

tracked controllers which reflected a user's movement accurately, allowing one to move through the virtual environment (VE) and manipulate virtual objects in it. All this is done to completely immerse users into a virtual world.

But what exactly does the term 'immersion' mean? Slater [40] describes immersion as the objective level of sensory fidelity a VR system provides [4]. A non-exhaustive list of factors that contribute to the level of immersion is found in Table 2.1.

Field of View	The size of the visual field (in degrees of visual angle) that can be viewed instantaneously.
Display Resolution	The resolution (number of distinct horizontal and vertical pixels) an HMD provides.
Stereoscopy	The display of different images to each eye to provide an additional depth cue.
Frame Rate	How many stereoscopic images are generated each second.
Software Factors	Factors influenced by software such as the realism of lighting, how a user interacts with the environment [35, 45], or the design of an avatar [15].

Table 2.1: Non-exhaustive list of factors that contribute to the level of immersion [4].

In contrast to immersion, the term 'presence' is described by Slater [40] as a subjective human reaction to immersion. Different levels of presence can be experienced with one and the same immersive system. In the future, immersion still has room for improvement because even today it is a challenge to appropriately stimulate senses such as olfaction (the sense of smell) or gustation (the sense of taste) [36]. Consequently, complete immersion into a VE is not yet possible.

Realistic haptic feedback in VR is also a major challenge. To provide this, controllers usually incorporate vibration actuators. This type of feedback is called active haptics as the unit actively exerts a force on the user based on information from the VE. However, vibration is very limited in providing a realistic feeling of haptics. Only some research models offer realistic haptics, but usually only for a specific domain, which causes them to be very inflexible [16, 28].

In contrast to active haptics, passive haptics do not apply an active force. Instead, the physical properties of an object (e.g., shape, weight, texture, temperature) are used to provide a sense of haptics, making them more lightweight, less complex, and cheaper [18]. This approach is usually realized by means of passive haptic proxies. These are real objects whose physical properties are used to imitate virtual objects from the VE, making them tangible [2]. They can be either gathered from the environment (e.g., use a real cup to represent a virtual one) or 3D-printed. The overall believability of a passive haptic proxy depends largely on how accurate its shape is, which is especially true for interactable parts like the handle of a cup, but also depends on the weight, material, and even temperature [39].

Parallel to VR, a concept called augmented reality (AR) has also been developed. Whilst VR completely replaces the real world and immerses someone into a virtual one, AR primarily shows the real world and modifies it with virtual elements, making it a blend of the physical and a virtual world. AR technology is often used in mobile applications with a famous example being Pokémon GO [7].

[7] https://www.pokemon.com/de/app/pokemon-go/

Both VR and AR can be classified through Milgram's Reality-Virtuality (RV) Continuum (Figure 2.2) [30] that depicts a scale ranging from reality to virtuality (i.e., a complete virtual environment). The area between these two extremes that mixes real and virtual elements is called Mixed Reality (MR).

Figure 2.2: Definition of the RV Continuum [30].

2.2 Avatars in VR

To be immersed even further into a VE, one also has to create a digital depiction of the user's own body in addition to an immersive environment. This self-representation, which one usually experiences from the first-person perspective, is called an avatar. The VR tracking system allows such avatars to move analogously to one's own body. An avatar can take many different forms. The visualization of the hands is the most important one functionally, as they provide the means of directly manipulating virtual objects [32]. That is why oftentimes just a pair of disconnected and thus floating hands is used as an avatar. However, some applications go one step further and visualize both arms or even a whole virtual body.

Avatars vary not only in terms of their appearance, but also in terms of their realism [32]. In addition to visually ranging from being abstract (e.g., a flat hand) or stylized (e.g., a robot hand) to a photo-realistic depiction of a human body, they can also incorporate the user's gender or skin colour so that it resembles the individual user as close as possible (Figure 2.3).

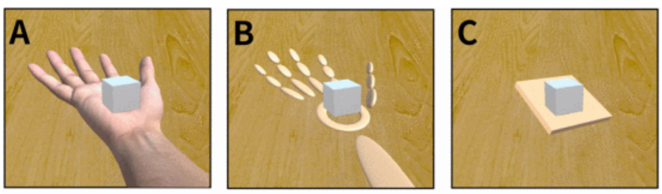


Figure 2.3: Examples of a realistic (A), semi-realistic (B), and abstract (C) hand model [32].

Consequently, we do not only perceive the VE, but also our virtual selves (i.e., one's avatar) and what impact we have on the VE. The feeling (or illusion) of an avatar being one's own body and thus being the source of all incoming sensations is called embodiment [15].

2.2.1 Avatar Embodiment

Embodiment includes multiple feelings, or self-attributions, of which the three most important are the following:

- **Body ownership (BO)**: The feeling of something being part of one's own body. The sense of BO can be strong even with a body that is not in the same location as your real one [15]. BO can also be attributed to supernumerary limbs (e.g., owning a third arm) or unusual limbs (e.g., owning elongated arms, a tail, or arms of different skin colour or different sizes) [10].

  Example: *You feel like the virtual hand is your own.*

- **Agency**: The feeling of directly causing changes in the environment and the ability to control the actions of one's body (i.e., one's avatar) [10].

  Example: *You feel like you can control a virtual hand as if it was your real one.*

- **Location of the body**: The feeling that the virtual body is collocated (i.e., in the same position) as the real one [15]. When real and virtual body parts are not collocated, a phenomenon called proprioceptive drift can occur, in which the perceived location of one's real body parts drifts toward the displaced virtual one [33].

  Example: *You feel like your hands are located where your virtual ones are.*

In both ecological but also experimental contexts, such feelings are essential to successfully achieve any kind of desired action. They enable the estimation of limb positions, provide feedback for tuning a variety of motor commands, provide important information for correcting and adjusting errors, and more [5].

This brings up the question of how one can measure such subjective feelings. Gonzalez-Franco and Peck [15] have developed a standardized avatar embodiment questionnaire based on 25 questions ranging from BO to agency to motor control and many more that can accurately measure these feelings. The questions can be adjusted or removed depending on the context of the study. An example set of questions regarding BO can be seen in Figure 2.4.

1. Body ownership.

Q1. "I felt as if the virtual _____was my _____"
If there is more than one avatar, e.g. in a VR social interaction, use a longer version: "I felt as if the virtual _____I saw when I looked down was my _____"
Q2. "It felt as if the virtual _____I saw was someone else"
Q3. "It seemed as if I might have more than one _____"
- If there is a mirror:
Q4. "I felt as if the virtual _____I saw when looking in the mirror was my own _____"
Q5. "I felt as if the virtual _____I saw when looking at myself in the mirror was another person"

Figure 2.4: An example set of questions regarding BO [15]. The gaps can be filled with information about the experiment.

Each question can be answered by rating a 7-Point Likert scale that provides responses from -3 (strongly disagree) to +3 (strongly agree) and also a neutral response (0). Ideally, these questions should be randomized to limit context effects. To emphasize the key aspects of embodiment the authors also created a formula[8] that measures the total embodiment based on the ratings of a completed questionnaire with $TotalEmbodiment = (\frac{Ownership \times 2}{5} + \frac{Agency \times 2}{4} + \frac{Location \times 2}{3} + \frac{TactileSensation}{4} + \frac{Appearance}{4} + \frac{Response}{5}) \div 9$

Nowadays, the embodiment questionnaire is used in many different studies that investigate those feelings in controlled experiments [22, 27, 33].

Avatar appearance also greatly affects the aforementioned feelings of BO and agency. Compared to an abstract representation, a realistic one causes a stronger sense of BO [1]. Since humans use their own body as a reference to internally measure the size of objects in their environment (a concept called body-based scaling [27]), the size of one's avatar also influences the size perception of virtual objects, especially if a realistic avatar, that causes a strong sense of BO, is used [32].

A strong sense of BO can also have an impact on continuous motor performances. In a study by Burin et al. [5] participants either saw themselves from a first-person perspective (1PP), causing a strong sense of BO, or a third-person perspective (3PP), causing a weak sense of BO. They were then tasked to draw a straight line in VR. What they did not know was that the virtual hand either performed the same action (i.e., drew a straight line) or deviated from one's movement by drawing an ellipse instead. The results for the deviating 1PP condition show, that the sense of BO stayed high in addition to the participants' hands even adapting to the virtual one causing them to ovalize their drawing of a line. This ovalization effect was shown to correlate with the sense of BO and thus was much weaker in the 3PP variant, which again shows the reciprocal influence of avatars and embodiment.

2.3 Redirected Movements

While avatars aim to enhance immersion and give you more control over your virtual body, the redirection of body movements aims to solve some of VR's other challenges such as non-immersive haptics [2], space restrictions [35, 45], or tiring overhead interactions [11]. To achieve this, a technique originating from 2D mouse pointing tasks [7] is used, where one modifies the mapping between physical mouse movements and the proceeding digital mouse movements. This is also known as modifying the control-display (CD) gain resulting in an acceleration or deceleration of mouse movements. Similarly, one can modify the CD gain in VR applications, which changes the mapping between real and virtual movements [9], resulting in what is called redirection. The following modifications are possible:

- **CD gain of 1**: This is the baseline and results in a one-to-one mapping between real and virtual movements, as is the case when not using redirection at all.
- **CD gains bigger than 1**: Movements are amplified which results in higher speeds and helps at reaching remote objects [35, 45] by extending the user's reach in the virtual space, which is especially helpful in small-scale VR setups. However, it comes with the disadvantage of being less precise, as small movements are automatically amplified to bigger ones [9].
- **CD gains smaller than 1**: Movements are reduced which results in lower speeds and helps in completing precise tasks [9].

[8] The three latter feelings found in the formula are not relevant to this summary.

One application area of movement redirection is called redirected walking [26]. With this technique, you can make a user explore a practically infinite amount of space in the VE by guiding them on paths in the real world that differ from the paths perceived in the virtual world. This is achieved by subtle manipulations of the virtual camera (i.e., the virtual head). However, for this to work without the user noticing, a quite large VR area is needed. Steinicke et al. [41] found that you need a radius of at least 22m to make the redirection unnoticeable to a user. However, more recent studies shrunk that space need down drastically by using coupled curved paths that enable continuous walking in the VE instead of using straight paths [26].

This begs the question of why redirection can be applied without the user noticing the resulting visual-proprioceptive conflicts (i.e., the conflict between what you see and the sense of self-movement or the sense of knowing the position of your body).

2.3.1 Visual Dominance

An effect called visual dominance [14] makes it possible to apply redirection without a user noticing, stating that vision dominates other modalities. This is especially true for senses, that have a lower spatial resolution than vision such as proprioception [6]. Visual dominance can result in different illusions, an example being the well-known rubber-hand illusion (RHI) [20]. Here, a subject places both hands on a table next to each other with one hand being visually obscured. A realistic-looking hand made from rubber is then placed where the obscured hand would be. If the rubber hand is then being stroked while simultaneously and synchronously doing the same to the unseen hand, a relocation of the hand is induced which results in the subject feeling as if the rubber hand was their own hand. In other words, the subject develops a strong sense of BO towards the rubber hand.

In this case, the illusion works through the specific combination of the visual and tactile senses. However, it is also possible to induce it with the visual and proprioceptive sense and thus without the tactile sense [10]. This effect is used in VR to create the virtual-hand illusion (VHI). When visual and proprioceptive information is being applied synchronously, a strong sense of BO is elicited towards the virtual hand [37]. This makes you feel like the virtual hand is your real one as is the case with the RHI. This effect can also be applied to other body parts as long as the visual-proprioceptive stimuli remain synchronous [22]. However, the VHI starts to fall apart as the stimuli become more incongruent and thus no longer plausibly fit together. An overview of the most inhibiting factors can be found in Table 2.2.

Matching stimuli	The stimuli should be synchronous (temporal), collocated, and have the same orientation (e.g., stroking the index finger synchronously and in the same direction on both the virtual and real hand.)
Anatomical plausibility	The artificial limb must be in a plausible posture (position and orientation) with respect to the body.
Identity	The limb must have a familiar appearance and shape.
Connectivity	The limb should be visibly connected to the body.

Table 2.2: Overview of the most inhibiting factors regarding the VHI [10].

The exploitation of visual dominance allows certain body parts to be redirected without users noticing it, a prominent example being the hands. This allows to improve haptics in VR with a concept called haptic retargeting.

2.3.2 Haptic Retargeting

Haptic Retargeting was introduced by Azmandian et al. [2] and allows a single physical prop to provide haptic feedback for multiple virtual objects. This is accomplished by dynamically aligning physical objects (i.e., physical proxies) and virtual objects (e.g., the virtual hands) while a user is interacting with the environment. Directing a user's real hand to a desired location and aligning it with a real physical proxy is possible due to visual dominance [14], which leads to a compensation by the user when the virtual hand is being redirected [47]. The authors proposed three different approaches to accomplish the alignment:

- **Body warping**: Manipulate the avatar (i.e., the hands) such that a virtual body part appears to be at the virtual target object when the real hand makes contact with the real target.

- **World warping**: Manipulate the coordinate system of the VE in a way that the alignment happens. Object shapes might be distorted [47].

- **Hybrid warping**: Dynamically combine Body- and World Warping to create an alignment.

To avoid possible disruptions during Body Warping, the warp is not applied instantaneously, but incrementally (with an exception being Blink-Suppressed Hand Redirection [48]). This results in the virtual hand being in the same position as the real one at the start of the warp and aligned with the target when it is reached. The incremental warp is defined by a warping ratio α that determines the amount of warp applied to the hand's position while it is progressing toward the target:

$\alpha = max(0, min(1, \frac{(W_T - W_O).(P_H - W_O)}{(W_T - W_O)^2}))$,

with P_H being the hand position, W_O being the hand position at the start of the warp (warp origin) and W_T being defined as the warping end. The arm and hand must also be translated and rotated around the user's body position so that the arm does not appear detached from the torso.

To compare these three techniques, the authors analysed the paths of the participants' hands while reaching for a cube. These paths should be direct, straight, and without any correcting movements (also called kink; Figure 2.5), otherwise there is not a good agreement between reality and the virtual world. Hybrid warping accomplishes the highest sense of presence while world warping had the most direct path to targets with body warping causing the most corrections near a target. A visual example of haptic retargeting can be found in Figure 2.6.

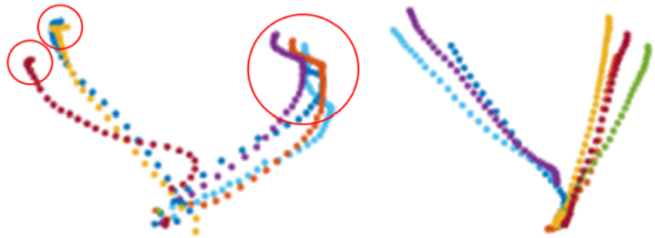


Figure 2.5: Path examples that show a kink (left) and no path correction (right)

Figure 2.6: The user touches 3 different virtual cubes while in reality he is always redirected to the single physical cube (Also called: 1 in 3 Illusion) [2].

2.3.3 Other Types of Hand Redirection

Other types of hand redirection also exist, each with different use cases. Firstly, there is a distinction between redirection with and without a target. While redirection with a target changes the trajectory of the hands depending on the relative position of the hand and the target to each other making it possible to continuously guide the hand in the direction of a target, as mentioned in section 2.3.2 [2], redirection without a target simply applies a general offset to the virtual hands [45, 35]. This offset can be applied in all three dimensions, meaning gain-based (i.e., forward and backward movements), horizontally or vertically [47] (Figure 2.7).

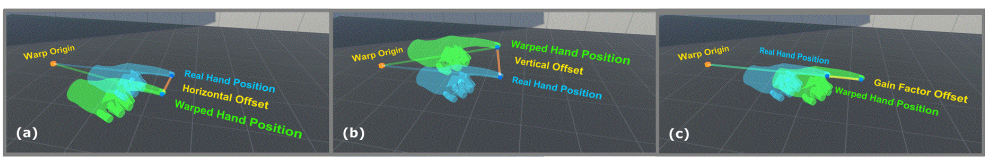
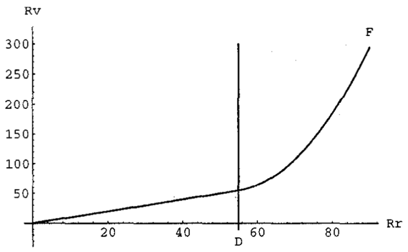


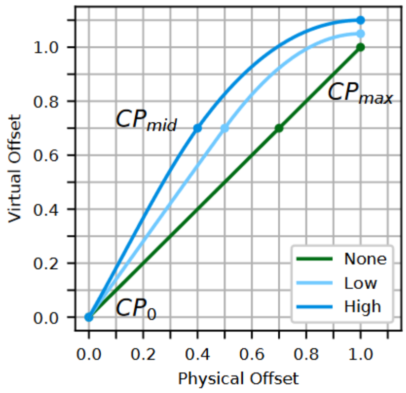
Figure 2.7: Visualization of hand redirection being applied in three different dimensions: (a) Horizontally, (b) vertically, and (c) gain-based [47].

Additionally, the mapping between real and virtual hand movement does not necessarily have to be linear. The Go-Go Interaction Technique developed by Poupyrev et al. [35] uses a mapping function that remains linear until a certain distance D is reached (usually 2/3 of the arm length), after which it grows exponentially (Figure 2.8a). This technique allows a user to extend their reach immensely but comes at the cost of weakening the sense of BO.

This is where Reach-Bounded Non-Linear Input (RNL) Amplification by Wentzel et al. [45] tries to improve upon. RNL Amplification does not extend one's reach to the same degree as the Go-Go Interaction does as it primarily amplifies smaller movements, but it tries to retain a strong sense of BO. The resulting mapping function is a hermite curve, that starts with no amplification, then grows steadily until it becomes weaker at the end again. Furthermore, the hermite curve can be tuned for different amplification levels (Figure 2.8b). It comes with the disadvantage of first having to calibrate the system before use by defining the maximum reach and a neutral point, but the authors claim that this process could be automated.



(a) Go-Go interaction technique mapping function that consists of a linear and an exponential part [35].



(b) RNL amplification mapping functions with high and low amplification determined by a hermite curve [45].

Figure 2.8: Two different types of mapping functions for hand redirection.

Hand redirection allows the VR experience to be enhanced in different meaningful ways. Firstly, it enables users to significantly extend their reach by amplifying forward and backward motions [35, 45] and to prevent the virtual hands from penetrating other virtual objects [33, 49]. Notorious overhead interactions in VR, where the relatively heavy HMD presses down on one's face, can also be made less tiring using this technique [11]. Additionally, hand redirection enables the modification of perceived properties of a physical object (e.g., shape), while a user is continuously exploring and touching its surface. Kohli [24] explores this idea of haptic distortion by placing a real, flat table in the environment. This flat table was then made to feel curved, sloped, and tapered by distorting the motion of a user's virtual hand relative to the real hand, making it possible to feel a virtual object that is different from its physical counterpart (Figure 2.9).

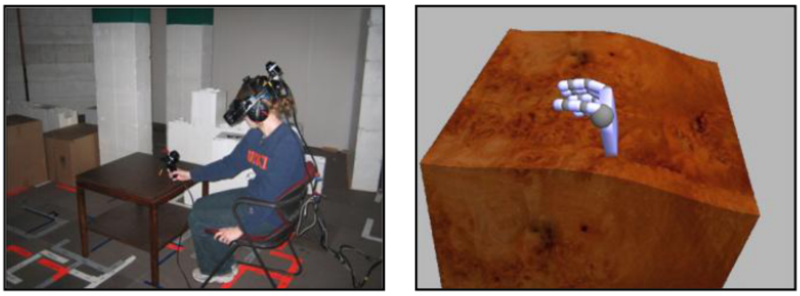


Figure 2.9: A real, flat table (left), feels distorted in VR (right) by redirecting the hand [24].

As the amount of redirection is increased causing the visual and proprioceptive sense to diverge, the more likely it is for a user to start noticing that their hands are being redirected.

2.3.4 Hand Redirection Thresholds

These hand redirection detection thresholds (HRDTs), in which a user does not notice their hand being redirected, are influenced in different ways. In a study by Zenner et al. [47] it was found that the virtual hands can be redirected by 4.5° either horizontally or vertically and in each direction without users noticing. Gain-Based redirection stays undetected with a CD gain between 0.88 (6.18% less far than the virtual hand) and 1.07 (13.75% farther than the virtual hand).

HRDTs are not static, as the appearance of one's avatar influences them [33]. It was found that realistic hand-avatars can extend HRDTs by up to 31.3% (i.e., making redirection easier to miss) with the effect getting stronger the more realistic and individually fitting (e.g., having the same skin colour) an avatar gets and thus accurately represents a subject's body. However, this increase only applies to a leftward shift on the right hand (and presumably to a rightward shift on the left hand, but this was not tested). Additionally, the proprioceptive drift gets higher with a realistic avatar [33]. This indicates that visual information was given an even higher priority during visual-proprioceptive conflicts in realistic avatars.

These findings demonstrate that the appearance of the avatar greatly influences HRDTs. However, we are not aware of any paper that combines a full-body avatar with hand redirection in VR. Still, there are papers that address extended arms in VR and also a study that uses hand redirection with a virtual arm, but in AR.

2.4 Combining Full Body Avatars and Hand Redirection

Feuchtner et al. [10] conducted an experiment using an AR setup, where a user could remotely control devices with a virtual arm, that extends way beyond the real-world counterpart. Among other conditions, they dynamically painted out the real arm and hand that were still visible through the cameras and only showed the virtual arm. The function that amplified hand movements was based on the aforementioned Go-Go interaction technique [35] with D=0.408 (i.e., amplification started at a distance of ~40% of the user's arm length).

The hand and arm were visually realistic which resulted in a strong sense of BO and caused participants to feel like their real arm was becoming longer. Even after the experiment, they felt like the arm that was extended in VR was still elongated in real life compared to the other arm. Agency ratings were also strong in this condition. Most participants (67%) preferred visualizing the whole arm instead of only showing a floating hand with reasons being that the hand feels more connected and that the arm is a helpful depth cue that makes navigation easier. This study shows, that it is possible to retain a strong sense of BO and agency while redirecting a whole arm. However, it is also important to state that this study was conducted in AR rather than VR which causes a different sense of immersion since one primarily sees the real world and additionally requires users to constantly wear a green glove to paint out the real arm in AR.

A VR study by Kilteni et al. [22] shows similar findings. Although redirection was not used, they still extended a single arm to different lengths with the maximum being quadruple one's arm length (Figure 2.10), while keeping visual-tactile stimulation synchronous. With that synchronicity being present, a strong sense of BO was preserved with an arm length of up to 3 times longer than the original arm.

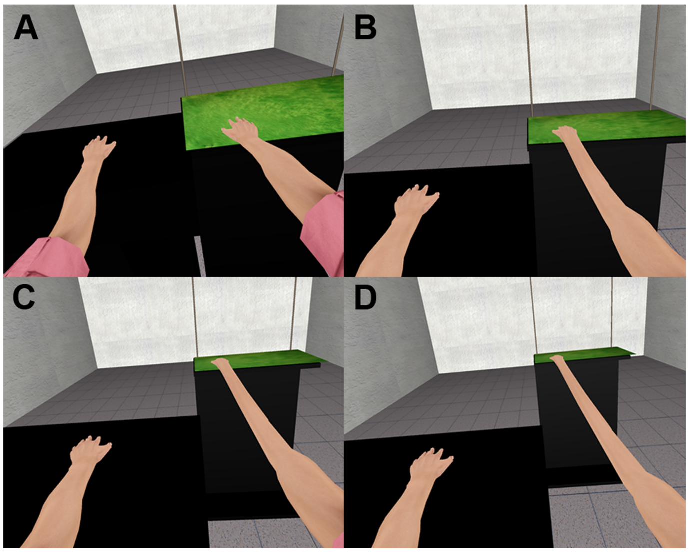


Figure 2.10: (A) Both virtual arms were of the same size as the participant's arms. The right arm was elongated to (B) double, (C) triple, or (D) quadruple the true length [22].

These studies show that even more complete avatars that visualize more features of the human body than just the hands can be altered in significant ways while still keeping a strong sense of BO and agency.

2.5 Summary

In summary, redirection of movements can greatly enhance a VR experience in several ways, including more efficient use of limited VR space [35, 45], increased interaction speed or precision [9], and even a more realistic haptic experience [2]. However, there are thresholds for the detection of redirection in which users should remain [47] to ensure that they do not notice that redirection is present which would cause a break in immersion. It was also shown that avatars influence HRDTs, with more realistic ones making redirection easier to miss [33]. This is supported by the fact, that missing connectivity of the virtual hand to the user's body can disrupt the ownership illusion [10].

However, it is not yet known how an avatar that visualizes and simulates the user's entire body (independent of its visual realism) would impact the sense of embodiment and HRDT-values because, to our knowledge, VR research has not yet combined full-body avatars and hand redirection (HR). Similarly, to our knowledge, there is also no research on how the pure completeness of an avatar, independent of its graphical realism, influences the sense of embodiment. It is for these reasons that we decided to conduct our own study to explore how the sense of embodiment and HRDTs are affected by increasingly complete (i.e., "full") avatars.

Chapter 3
Concept

As stated in our research questions, our goal is to better understand the impact of more complete avatars on the sense of embodiment and hand redirection detection threshold (HRDT). In doing so, we would like to focus on the following aspects: To investigate the relationship between HRDTs and the completeness of an avatar, we first want to investigate whether a higher avatar completeness corresponds to a higher sense of embodiment independent of the avatar's realism. Based on this result we want to examine if and how HRDTs are affected by more complete avatars and possibly a higher sense of embodiment. To accomplish this, we designed the following concept.

3.1 Avatar Visualisation

3.1.1 Avatar Completeness Level

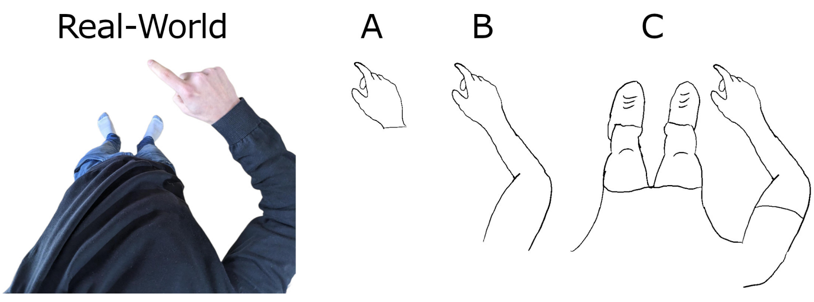


Figure 3.1: First-Person-Perspective of different avatar-completeness levels. Only the right side of the body is shown.
A = Only Hands, B = Hands with lower and upper arms, C = Full-body avatar.

Avatars can be designed in many different ways, as seen in Section 2.2. In order to investigate how the completeness of an avatar (i.e., how much of the virtual body is visualised) could affect embodiment and HRDTs, we defined three different avatar-completeness levels (ACLs) (see Figure 3.1):

- **ACL-1**: Avatars belonging to this level only visualize the hands, or objects that act as hands (i.e., abstract cubes acting as hands). They visualize only what is necessary to enable interactions with a virtual environment (VE). These avatars are the most commonly adopted in current virtual reality (VR) systems and are often used as the baseline for research.

- **ACL-2**: Avatars belonging to this level visualize upper and lower arms in addition to hands. They not only visualize what is absolutely necessary to enable interactions with a VE, but also connect the points of interaction (i.e., the hands) to the user in a natural way using arms. We defined this level that way because such avatars are also commonly used in VR applications, albeit not as frequently as those belonging to ACL-1.

- **ACL-3**: Avatars belonging to this level visualize a complete humanoid body (i.e., full-body avatar). They are harder to implement than those belonging to lower ACLs, since one has to track more body parts (e.g., feet) or compensate for missing tracking information through other means (e.g., using inverse kinematics (IK) which will be explained in Section 4.3). It is rare for VR applications to use an intermediate of ACL-2 and ACL-3[9].

In the study, a HRDT must be determined for each participant and ACL. The exact study design used to obtain these data will be explained in Section 5.

3.1.2 Avatar Graphics

For the study, we will use an abstract 3D avatar model each for ACL-1, ACL-2, and ACL-3. Since we are initially only concerned with the effects of avatar-completeness on HRDTs, we will try to omit other influences by colouring these avatars white and designing them in a gender-neutral way.

However, since it would also be interesting to investigate how an abstract full-body avatar would affect HRDTs compared to a full-body avatar with realistic textures and shape, we have decided to assign two additional models to ACL-3: A realistically textured full-body model with a male and female version. Thus, we could also compare these results to the study by Ogawa et al. [33], where they found that more visually realistic avatars make hand redirection (HR) harder to notice.

In the study, the avatars must also be adjusted to the proportions and lengths of the participant's limbs, which is particularly important for the full-body avatars. After all, a significantly larger avatar or one with incorrect arm proportions would weaken the embodiment feeling drastically if visual-tactile stimulation is not kept synchronous [22].

[9] An exception can be found in the home screen of Meta Quest devices, where ACL-2 avatars are visualized together with a torso, but (for now) without legs.

3.1.3 Avatar Movement

As soon as a participant enters the virtual world, embodies an avatar, and begins to perform any task, this avatar must also be animated in such a way that it moves in exactly the same way as the participant. Otherwise, the participant would not be able to complete any task in a controlled manner. Of course, this does not include the hand movement when HR is being applied. Since we are investigating HR, the movement of the hand or even the arm may be changed in this case.

3.2 Assessing Avatar Embodiment

As mentioned above, we want to collect embodiment ratings in addition to HRDTs for each ACL. The embodiment questions are based on the standardised embodiment questionnaire by Gonzalez-Franco and Peck [15], which was explained in more detail in section 2.2.1. Originally, this questionnaire contains 25 questions. For our study, we have reduced this number to 15 questions applicable to our study, as we do not have any external stimuli or tactile sensations. Our selection of questions for the embodiment questionnaire can be seen in Figure 3.2.

1. I felt as if the virtual right hand was my real hand.
2. It felt as if the virtual right hand I saw was someone else's.
3. It seemed as if I might have more than one right hand.
4. I felt as if the virtual right hand I saw when looking in the mirror was my own hand.
5. I felt as if the virtual right hand I saw when looking at myself in the mirror belonged to another person.
6. It felt like I could control the virtual right hand as if it was my own hand.
7. The movements of the virtual right hand were caused by my movements.
8. I felt as if the movements of the virtual right hand were influencing my own movements.
9. I felt as if the virtual right hand was moving by itself.
10. I felt as if my right hand was located where I saw the virtual right hand.
11. I felt out of my body.
12. It felt as if my real right hand was turning into an avatar hand.
13. At some point it felt as if my real right hand was starting to take on the posture or shape of the virtual hand that I saw.
14. At some point it felt that the virtual right hand resembled my own real hand in terms of shape or skin tone or other visual features.
15. I felt like I was wearing different clothes from when I came to the laboratory.

Figure 3.2: Our selection of 15 questions regarding the sense of embodiment. The underlined words indicate gaps we have filled with information about our study.

To ensure that the answers to the embodiment questionnaire and HRDT-results were not biased by nausea or motion sickness in VR, participants will have to answer the widely adopted simulation sickness questionnaire (SSQ) created by Bimberg et al. [3] in which the participants rate how pronounced 16 symptoms divided into 3 categories (nausea, oculomotor disturbance, and disorientation) are to them. The complete SSQ can be found in Appendix C.

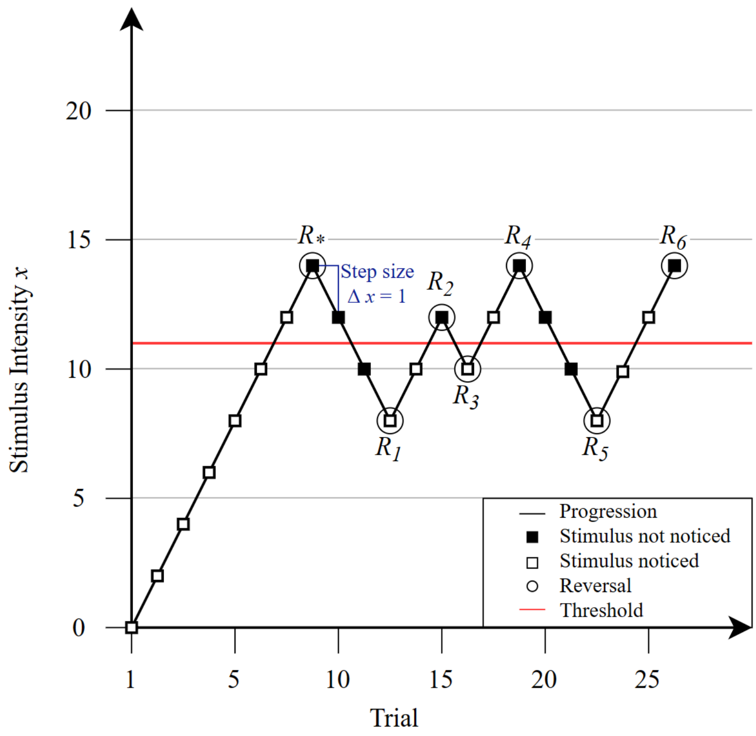


Figure 3.3: Visualisation of a generalized staircase procedure with a single sequence[10].

3.3 Staircase Procedure

In order to determine HRDTs for each participant and each condition, we intend to deploy a staircase procedure which is an adaptive method of psychophysics designed for measuring perceptual thresholds [13].

In a simple staircase procedure, participants are repeatedly exposed to a stimulus of varying strength, in our case, HR-strength. It starts with exposing a participant to the minimum stimulus (or the absence of a stimulus) and increases it until it is noticed (see Figure 3.3). Now a reversal takes place and the stimulus decreases until it is not noticed anymore, which results in another reversal. The difference between two stimuli is called the step size and can also be described as the resolution of the procedure. This process is repeated until the desired number of reversals is reached. Alternatively, a staircase procedure can also start with the maximum stimulus, which should be easy to detect.

Another possibility is to start a staircase procedure with two sequences. One sequence starts with the minimum stimulus and the other with the maximum stimulus. Thus, one sequence represents the progression of a simple staircase procedure as seen in Figure 3.3. Both sequences run in parallel during the procedure and it is completed when *both* sequences have undergone the desired number of reversals. The sequence providing the current stimulus is determined randomly with a probability of 50% until one of the two sequences has completed all its reversals.

[10]Image is based on the work of Kuehner [25].

A staircase procedure with several sequences has the advantage that the course of the procedure is not easily observable to participants. In a procedure with a single sequence, it can be relatively easy for a participant to tell when the stimulus is increasing or decreasing. Multiple sequences help to hide this process and avoid biasing in the results. To determine the final threshold, the mean of reversals R_1 to R_n is calculated [43].

Chapter 4
Implementation

We have developed a system that allows equipping a user with arbitrary avatars of all avatar-completeness levels (ACLs). Initially, an avatar exactly mirrors the movements of the real user, but by implementing hand redirection (HR), the right hand can be redirected to various degrees. It is also possible to adjust the size of the avatar and the length of its limbs to match the user's body. Our system was implemented using Unity3D[11] (version 2021.3.10f1), C# and a variety of Unity-Packages.

4.1 Packages

1. **SteamVR Plugin**[12]
   This package is used to interface with SteamVR and to handle input from the head-mounted display (HMD), controllers, and trackers.
2. **Unity Experiment Framework**[13]
   This package is used to streamline the creation of experiments and to log data acquired from the user study.
3. **Hand-Redirection-Toolkit**[14]
   This package provides implementations of popular redirection algorithms and is used to easily implement hand redirection.
4. **Unity Staircase Procedure Toolkit**[15]
   This package is used to easily implement an adaptive staircase procedure.
5. **VRQuestionnaireToolkit**[16]
   This package provides virtual, interactive questionnaires and is used to show the embodiment questionnaire to participants in virtual reality (VR).

[11]https://unity3d.com/
[12]https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647
[13]https://github.com/immersivecognition/unity-experiment-framework
[14]https://github.com/AndreZenner/hand-redirection-toolkit
[15]https://github.com/AndreZenner/staircase-procedure
[16]https://github.com/MartinFk/VRQuestionnaireToolkit

6. **Final IK**[17]
   This package provides inverse kinematics solutions and is used to properly animate all avatars. It also provided the model used as our abstract avatars.

7. **Microsoft Rocketbox Avatar Library**[18]
   This package offers a variety of human avatars, of which we use one male and one female version as a realistic full-body avatar.

4.2 Hand Redirection

For the implementation of HR, we used the hand redirection toolkit mentioned above. We used Cheng et al.'s [8] body warping algorithm for applying continuous HR. Parameters such as the warp origin or the desired HR-strength can be adjusted as desired.

4.3 Inverse Kinematics

A full-body avatar must not only visualise a whole body but also be animated congruently with the user's movements. This would be possible, for example, with a full-body tracking suit [23] or cameras paired with a neural network [46]. However, animating a full-body avatar with ACL-3 is also possible with only an HMD and four trackers, two of which are placed on the hands and two on the feet. Through a mathematical algorithm called inverse kinematics (IK), the posture of the entire body can then be interpolated. On the contrary, avatars belonging to ACL-1 or ACL-2 only require two trackers, which are placed on the hands, since the torso and lower body parts are not visualized. Our system does not support finger tracking, however, this could be added in a future study with other tracking systems such as Leap Motion[19] or Meta's hand tracking[20] used in the Meta Quest 2[21].

To enable this, a virtual avatar is equipped with bones, just like a real person (see Figure 4.1). The parameters of these bones (e.g. position and rotation) can be modified by the IK process. The 3D coordinates of all tracked body parts are used for the input, from which joint angles of all virtual limbs are calculated and interpolated. This means that we can give the position of the head (using the HMD) and the hands (using controllers or trackers) to the IK process, with which it can calculate how the other bones in the chain (e.g., upper and lower arm) should be translated and rotated to achieve a realistic body posture[22].

[17] https://assetstore.unity.com/packages/tools/animation/final-ik-14290
[18] https://github.com/microsoft/Microsoft-Rocketbox
[19] https://www.ultraleap.com/product/leap-motion-controller/
[20] https://www.meta.com/en-gb/help/quest/articles/headsets-and-accessories/controllers-and-hand-tracking/hand-tracking-quest-2/
[21] https://www.meta.com/de/en/quest/products/quest-2/
[22] A detailed description of the utilized IK-algorithm can be found here: http://root-motion.com/2016/06/inverse-kinematics-in-dead-and-buried/

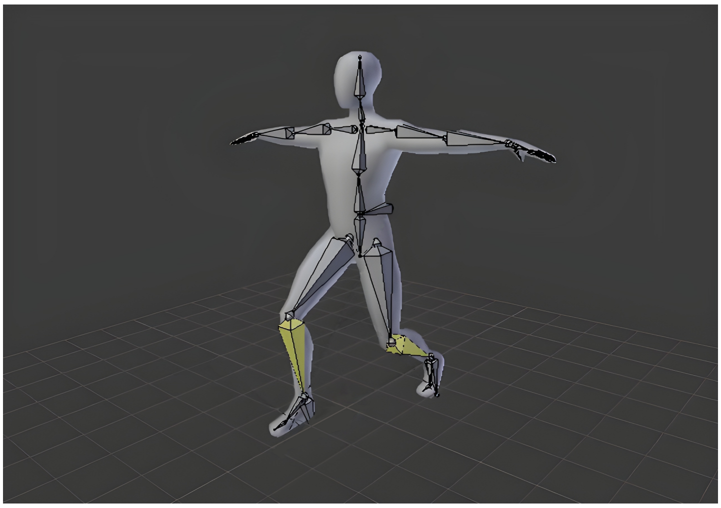


Figure 4.1: A humanoid model equipped with bones[23] which can be used by the IK-algorithm to create any pose.

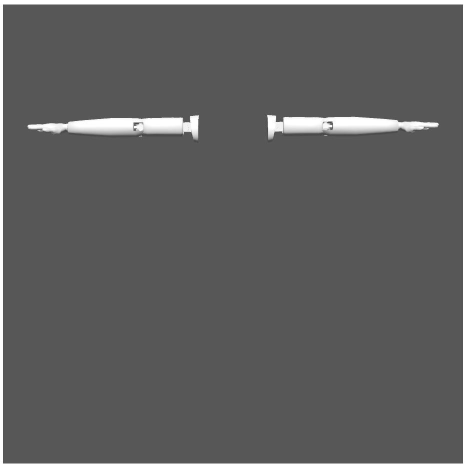
4.4 Avatar Design

To visualise all five avatars, we used the following 3D models and coupled them with the Final IK package. The hand avatar (see Figure 4.2a/4.2b), arm avatar (see Figure 4.2c/4.2d), and abstract full-body avatar (see Figure 4.2e/4.2f) were all taken from the Final IK package, which includes a crash-test dummy model that we coloured white. The realistically textured full-body models with a male (see Figure 4.1g/4.1h) and female version (see Figure 4.1i/4.1j were taken from the Microsoft Rocketbox Avatar Library.

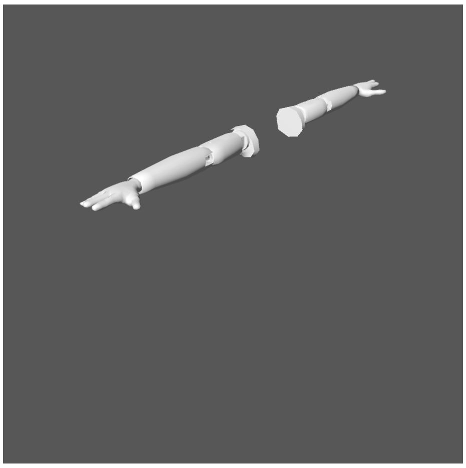
[23]https://cgi.tutsplus.com/tutorials/building-a-basic-low-poly-character-rig-in-blender–cg-16955

(a) Hand avatar (ACL-1) from the front.

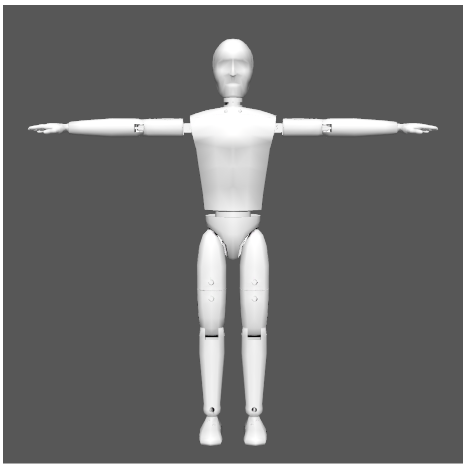
(b) Hand avatar (ACL-1) from the side.



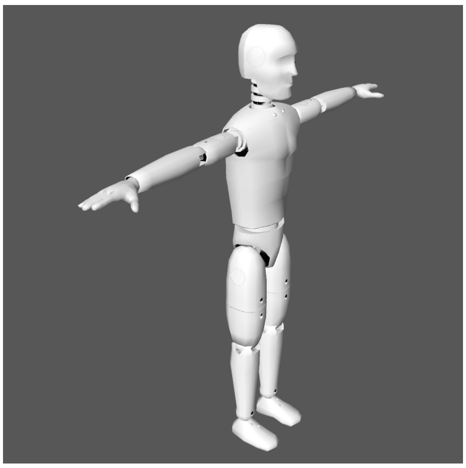
(c) Arm avatar (ACL-2) from the front.



(d) Arm avatar (ACL-2) from the side.



(e) Abstract full-body avatar (ACL-3) from the front.



(f) Abstract full-body avatar (ACL-3) from the side.

(g) Realistic full-body avatar (Male; ACL-3) from the front.

(h) Realistic full-body avatar (Male; ACL-3) from the side.

(i) Realistic full-body avatar (Female; ACL-3) from the front.

(j) Realistic full-body avatar (Female; ACL-3) from the side.

Figure 4.1: All avatars that were used in our experiment ranging from ACL-1 to ACL-3.

4.5 Avatar Scaling

Especially for avatars with an ACL of 3 (i.e., full-body avatars), it is essential to match the size of the avatar's body and limbs to the user's real body. To give an example, if the virtual arms are too long, you can no longer stretch them out fully; if they are too short, the virtual arm can be stretched out before the user has fully stretched out their real arm. In order to avoid such breaks in the immersion, we have developed an editor tool with which we can individually scale the height, upper arm length, lower arm length, and hand length of all avatars as seen in Figure 4.2 and 4.3. Since avatars are now scaled to exactly match the proportions of the participants, it is also not necessary to apply synchronized visual-tactile stimuli to keep the sense of embodiment from decreasing [22].

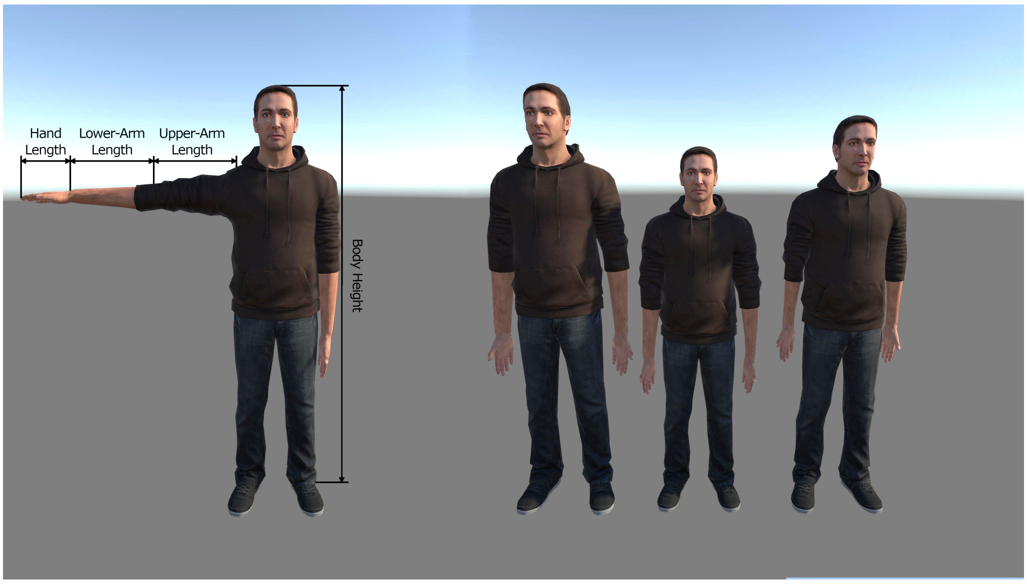


Figure 4.2: Left: Body parts that can be individually scaled.
Right: Example of the same avatar being scaled to three different proportions.

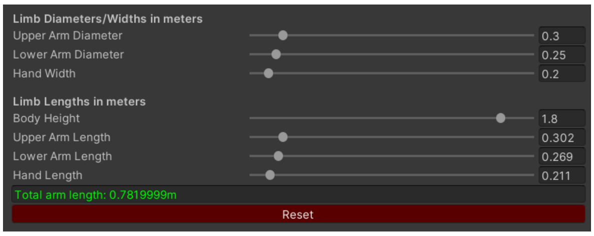


Figure 4.3: Avatar scaler editor tool that allows a variety of body parts to be scaled independently in order to match the avatar as closely as possible to the real body.

Chapter 5
User Study

5.1 Introduction

We conducted an experiment using a staircase procedure to study how hand redirection detection thresholds (HRDTs) change with different levels of avatar-completeness.

In the experiment, each participant embodied four different avatars derived from all three avatar-completeness levels (ACLs). With each avatar, they were exposed to different amounts of hand redirection (HR) or no HR at all while performing mid-air forward motions with their right hand. After each forward motion, participants had to judge whether HR was applied or not.

Prior to the experiment, participants were given a detailed explanation of how HR works and how to recognise it, both verbally and in an interactive demonstration. Therefore, all scenarios are considered very conservative and represent a worst-case scenario for detecting the presence of HR. As a result, real-world (i.e., in a non-clinical setting) thresholds will inherently be higher due to factors such as distraction, inattentiveness, etc. From the collected data, we can ultimately determine a HRDT for each individual participant and each avatar. The data from each participant using each avatar can then be aggregated and HRDTs can be compared between different ACLs to determine if an upwards trend really exists. Developers can utilize these results as a baseline to adjust the redirection employed in their applications. The experiment is described in detail in the following sections.

5.2 Hypotheses

To answer our two research questions (see Section 1.2), we transformed them into the following hypotheses:

H. 1 *A higher ACL leads to a stronger sense of embodiment.*

With **H.1** we want to investigate whether a more complete avatar really provides a stronger sense of embodiment independent of its graphical realism. Based on **H.1**, we now formulate a second hypothesis. If **H.1** turns out to be true, we want to explore whether the higher sense of embodiment also leads to increased HRDTs.

H. 2 *A higher sense of embodiment leads to greater HRDTs.*

If **H.2** turns out to be true, it would mean that developers should always consider using avatars with the highest possible ACL when employing HR, since the probability of breaking immersion would be reduced. It would also mean that the current trend in commercial virtual reality (VR) applications to gradually adopt more complete avatars would automatically be accompanied by the ability to use stronger HR without increasing the risk of breaking immersion.

5.3 Conditions

Every participant completed the task with four different avatars, each with a different ACL.

- An abstract hand avatar (ACL-1; see Figure 4.2a/4.2b)
- An abstract arm avatar (ACL-2; see Figure 4.2c/4.2d)
- An abstract full-body avatar with a single version for both male and female participants (ACL-3; see Figure 4.2e/4.2f)
- A realistic full-body avatar with a male and female version selected according to the gender of the participant (ACL-3; see Figure 4.1g/4.1h/4.1i/4.1j)

5.4 Participants

A total of 20 volunteers participated in the study. All participants were between 20 and 30 years old ($M = 23.26\,years, SD = 2.6\,years$). All participants confirmed that they were right-handed, have normal or corrected-to-normal vision, and had no health issues that affected their proprioception. A total of 6 participants wore glasses or contact lenses.

Participants rated their experience with each of the following items on a 4-point Likert scale (no experience $\rightarrow$ 1-5 times per year $\rightarrow$ 6-10 times per year $\rightarrow$ >10 times per year):

1. VR in general ($M = 2.6, SD \approx 0.82, min = 2, max = 4$)
2. VR gaming ($M = 2.2, SD \approx 0.7, min = 1, max = 4$)
3. 3D object interaction ($M = 3.1, SD \approx 1.21, min = 1, max = 4$)

5.5 Apparatus

The following list contains all the equipment that was used during the experiment:

- HTC Vive Pro head-mounted display (HMD) (see Figure 5.1b)
- One HTC Vive controller (see Figure 5.1b)
- Three HTC Vive trackers (see Figure 5.1b)
- Two HTC base stations mounted on tripods (see Figure 5.1a)
- One pair of shoes each with a screw thread for mounting an HTC Vive Tracker (see Figure 5.1c)
- Fingersplint (see Figure 5.1c)
- VR-capable laptop
- Measuring tape

The application was developed using Unity 2021.3.10f1. The HTC Vive Pro was utilized as the HMD and the built-in speakers were used to provide auditory feedback after each successful interaction (see Figure 5.5). To track the position of the participants' feet a special pair of shoes with screwed-on HTC Vive Trackers was employed. An HTC Vive Controller was used to track the location of the left hand and to answer questionnaires (see Figure 5.2).

For tracking the right hand, we used a third HTC Vive tracker that was screwed onto a threaded fabric. This fabric was then attached to the back of the participant's hand using a Velcro fastener (see Figure 5.1c).

To make the participants feel comfortable and to avoid fatigue of the right index finger, we also attached a finger splint to the right hand (see Figure 5.1c) which allowed the participants to keep the index finger up without strain. In addition, the rigid structure of the splint ensures that participants could not move the index finger, keeping the distance between the back of the hand tracker and the fingertip constant at all times. This is important as the virtual position of the right index fingertip is calibrated at the beginning of the experiment by touching the circular trackpad of the left HTC Vive controller. The calibration also causes the virtual hand model to be aligned with the real hand.

(a) Demonstration of the experiment set-up. The participant is wearing each piece of equipment and is tracked by two HTC base stations.

(b) All the equipment worn by a participant during the experiment. This includes a tracked pair of shoes (top left), a tracked fabric and a finger splint (top right), the HTC Vive Pro HMD (bottom left), and an HTC Vive controller (bottom right).

(c) Finger splint and fabric attached to the right hand using a Velcro fastener. The hand is tracked by an HTC Vive tracker that is mounted on the fabric.

Figure 5.1: Equipment used during the study.

5.6 Virtual Questionnaires

As mentioned in Section 3.2, each participant had to answer multiple questionnaires during the study. We could have had participants answer the questionnaires using pen and paper outside of VR, as is usually the case. However, we preferred to avoid participants having to switch back and forth between the virtual environment (VE) and the real world several times during the study. For one, this requires more effort and can cause SteamVR to slightly shift the seating position, requiring it to be re-calibrated. More importantly, switching between VR and the real world can cause breaks in immersion. Removing the HMD and leaving the VE before answering an embodiment questionnaire could skew the answers. Therefore, we decided to use the VRQuestionnaireToolkit mentioned in Section 4.1. This toolkit allows us to display and answer many different types of questionnaires in the VE (see Figure 5.2). The results are conveniently stored in an Excel-sheet for later analysis.

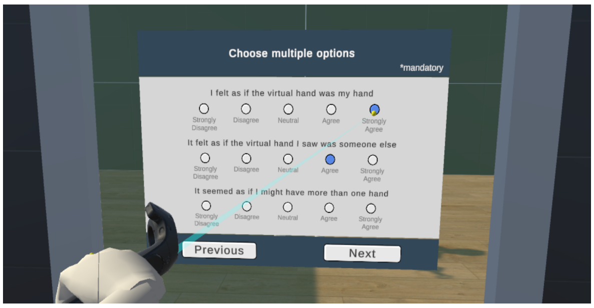


Figure 5.2: A participant can navigate through any questionnaire in VR and answer it by pointing the left controller to their desired answer and clicking the trigger. This allows participants to answer questionnaires without a break in immersion.

5.7 Procedure

After a brief welcome, our sessions began with handing out an information sheet (see Appendix D) and consent form (see Appendix E) to the current participant. After the consent form was signed, we explained the procedure of the experiment again, but this time verbally which also allowed us to answer any remaining questions. We then asked the participant to put on the tracked pair of shoes (see Figure 5.1b) and measured the participant's height (with shoes on), upper arm length, forearm length, and hand length. This was done in order to adjust the virtual avatars' height and arm length exactly to the dimensions of the participants' real body. After we entered this data into our application, we equipped the subject with the rest of the equipment, as seen above and asked them to sit on a chair. Since HR can be difficult to understand if you have never experienced it before, we first started a short demonstration of what will happen in the experiment, to make sure that the participant knows what HR is and can recognise it reliably.

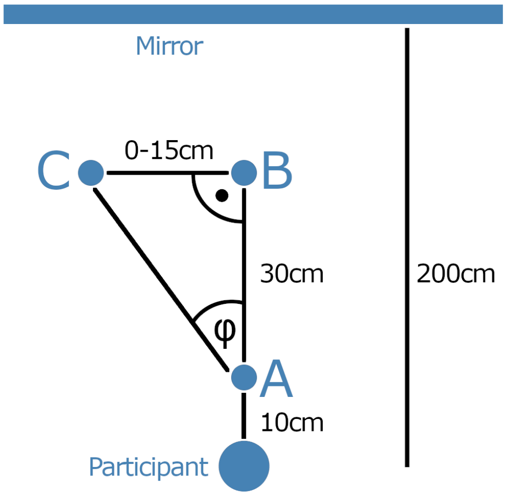


Figure 5.3: Diagram of the VE-Layout. A = Warp Origin, B = Virtual Target, C = Physical Target. A Participants' virtual hand travels from A to B, their physical hand from A to C. Theta ranges from 0° to 26.565°.

(a) Virtual mirror seen from a Third-Person-Perspective.

(b) Virtual mirror seen from a participant's point of view.

Figure 5.4: A participant can see their avatar in a virtual mirror.

In the VE, participants also sat in a chair and could see their virtual avatar (i.e., themselves) in a mirror (See Figure 5.4a/5.4b) which was positioned two metres away from them (See Figure 5.3). In front of their chest was a sphere (i.e., warp origin, with a radius of 1cm) which they had to continuously touch with their right virtual index finger for 0.5 seconds (see Figure 5.5). After successfully touching it, the sphere disappeared, whereupon another sphere appears 30 cm away. Participants then had to guide their right virtual index finger to the new sphere (i.e., virtual target) and continuously touch it again with their right virtual index finger for 0.5 seconds. From now on we refer to the movement from the warp origin to the virtual target as a *forward motion*, to which HR can be applied with different strengths. The HR-strength is controlled by an invisible sphere known as the physical target (See Figure 5.3). As the name suggests, this sphere is the target to where the physical hand is redirected to. The further away it is from the virtual target, the stronger HR will be. The physical target is shifted exclusively to the left with respect to the virtual target, by up to 15cm. As the HR-strength grows, the virtual hand is increasingly shifted to the right causing participants to compensate for this effect by moving their physical hand more to the left during a forward motion.

To redirect participants' hands we have used the body warping algorithm by Cheng et al. [8] which is defined by the following formula: $Warp = \alpha T$.
T defines the offset from the physical target (P_p) to the virtual target (P_v) and is calculated as follows: $T = P_v - P_p$. The value α defines the shift ratio from the start of a forward motion to the full offset T and ranges from 0 to 1. It is calculated as follows: $\alpha = \frac{D_s}{D_s+|H_p-P_p|}$. D_s defines the distance from the physical hand (H_p) to the warp origin (H_0) and is calculated as follows: $D_s = |H_p - H_0|$. In every frame the position of the virtual hand is calculated by adding the Warp value to the position of the physical hand: $H_v = H_p + Warp$.

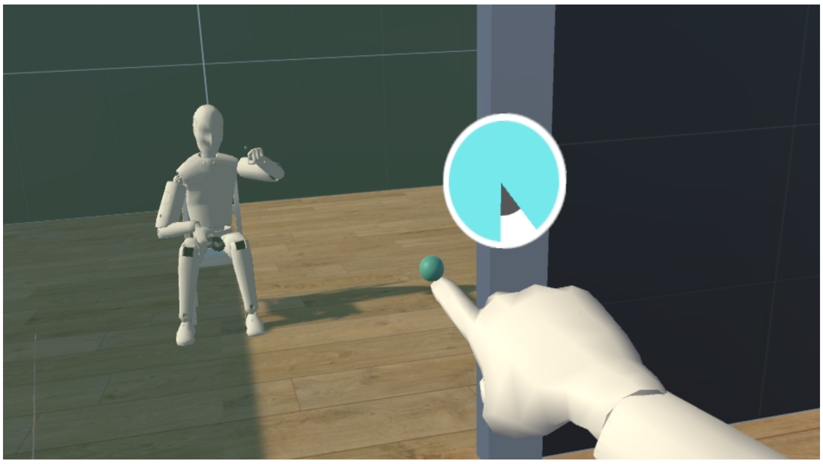


Figure 5.5: A participant has to continuously touch the spheres with their right virtual index finger for 0.5 seconds. The touch duration is visualised by a circle that fills up in 0.5 seconds. After the interaction has been successful and the circle has filled up, the HMD's built-in speakers provide auditory feedback in the form of a beep-noise.

The demonstration started with the participant doing a forward motion with their right hand without HR being applied. This was done in order to show the baseline and how regular movement without HR feels in VR. We then asked the participant to do another forward motion, but this time using the maximum HR-strength of 15cm, which each participant clearly noticed. To show that HR is not only on or off, but can also be applied in intermediate steps, we repeated forward motions with different HR-strengths until the participant and experimenter were sure that the task was understood and the real experiment could be started.

After that, the first block began. In total, there were four blocks, in each of which the avatar was changed so that each participant ended up using all four avatars. Each block has an identical structure, with the only difference being the current avatar, and consists of three tasks:

1. Firstly, participants had to do 5 forward motions without HR being applied. This is done to accustom the participant to their current avatar and to build up embodiment without HR affecting it.

2. In order to investigate **H.1**, participants had to answer the embodiment questionnaire (see Figure 3.2 and 5.2). They rated their impression of each of the items on a 5-point Likert scale ranging from *strongly disagree* to *strongly agree*.

3. In order to investigate **H.2**, participants had to repeatedly execute forward motions. This time, however, HR was applied according to the staircase-procedure with two sequences (see Section 3.3). After each trial, participants had to answer the following question with either yes or no: "Did the movements of your right virtual hand deviate from your real hand movements?". Thus, the answer yes indicates that HR was detected, and no indicates that HR was not detected.

To find a participant's HRDT for each specific avatar we initialized the aforementioned staircase-procedure with a step size of 1.5cm. In each trial, the procedure provided a new HR-strength. We used two sequences, the first starting with the minimum stimulus (absence of HR) and the second with the maximum stimulus (HR-strength of 15cm). The first sequence increased the HR-strength until the participant answered that HR was being applied. The second sequence decreased the HR-strength until the participant answered that HR was no longer being applied. After five reversals per sequence have taken place, the mean of the last 4 reversals per sequence was calculated. Averaging these 8 reversals then yields the HRDT for that particular participant and avatar. Then the next block with a new avatar began. The number of trials in each block could be different for each participant and was depended on how quickly each reversal was achieved. An example of the procedure can be seen in Figure 5.6.

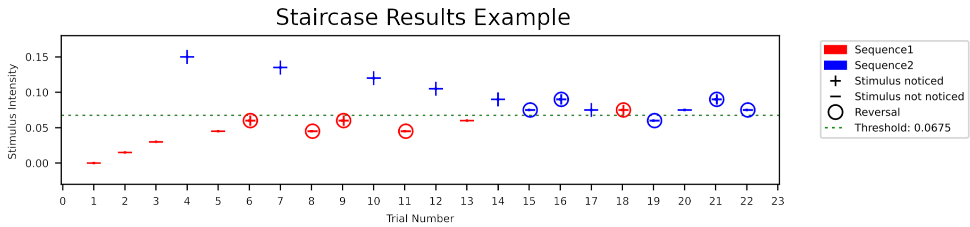


Figure 5.6: A graph that depicts an example staircase procedure with a final HRDT of 6.75cm. The y-axis shows the HR-strength, ranging from 0cm to 15cm (inclusive). The x-axis shows each trial, of which there were 22 in this example. The first sequence starts with a HR-strength of 0cm, the second starts with a HR-strength of 15cm. A '+' indicates responses stating that HR has been applied. A '-' indicates responses stating that no HR has been applied. Encircled answers indicate reversals, where the direction of a sequence is reversed. Each sequence goes through a total of five reversals, of which the last four are used to calculate the HRDT.

After the fourth block was finished, the participant's last task in VR was to answer the simulation sickness questionnaire (see Appendix C) which contains questions about how they physically feel after experiencing this VR application. Participants rated their symptoms for each of the items on a 4-point Likert scale (None → Slight → Moderate → Severe).

Afterwards, we helped the participants to remove the VR equipment. Before concluding the session, participants answered a final post-study questionnaire (see Appendix B) and were offered sweets to take away before they left.

The study procedure was reviewed and approved by the ethical review board of the faculty of Mathematics and Computer Science at Saarland University (see Appendix F).

5.8 Design

The study was based on a within-subject design. We distinguished two independent variables (IVs):

1. HR-strength ranging from 0cm to 15cm (inclusive; changed each trial)
2. Avatar completeness (hand vs. arm vs. abstract full-body vs. realistic full-body gendered; changed each block)

Four dependent variables (DVs) were measured:

1. Was HR detected by the participant? (after each trial)
2. HRDTs (after each block)
3. Embodiment questionnaire results (after each block)
4. Simulation sickness questionnaire (SSQ) results (once at the end of the session)

The order of the four conditions was counterbalanced across participants using a 4x4 Latin Square (see Figure 5.7).

1	2	3	4
3	1	4	2
2	4	1	3
4	3	2	1

Figure 5.7: A 4x4 Latin Square depicting which avatar order a participant will receive. 1=Hand Avatar, 2=Arm Avatar, 3=Abstract Full-Body Avatar, 4=Realistic Full-Body Avatar. Participant n receives the avatar order from row (n mod 4).

The forward motion was performed a different number of times for each participant ($M = 94.8, SD \approx 7.91, min = 85, max = 116$) and was dependent on when the two sequences of the staircase procedure reached five reversals resulting in a total of 1896 trials/samples with 20 participants.

5.9 Results

First, we will discuss the results of the subjective responses from the embodiment questionnaire and will propose a score for the general perception of embodiment based on a shortened version of our embodiment questionnaire. Then we will summarize the HRDT results for each avatar. Finally, we will discuss the results of the SSQ.

5.9.1 Statistical Tests

In the analysis, both the embodiment scores and the HRDTs are compared between our 4 conditions consisting of four avatars belonging to three ACLs. A suitable method for this type of analysis is the one-way repeated measures analysis of variance (ANOVA) [17]. Repeated measures are obtained when we measure the same variable repeatedly, in our case we measure embodiment scores and HRDTs with four different avatars.

A prerequisite for using ANOVA is the fulfilment of the following assumptions[24]:

- **Outliers assumption:** There must be no significant outliers. They can be identified by using box plot methods.
- **Normality assumption:** The outcome (or dependent) variable should be approximately normally distributed. This can be checked by using the Shapiro-Wilk test [38] at $\alpha = 0.05$ for each condition.
- **Assumption of sphericity:** The variance of the differences between groups should be equal. This can be done by using Mauchly's test [29].

To reveal specific differences among our four conditions, we use the Holm-Bonferroni method for post-hoc analysis. In the case of the normality assumption not being fulfilled, one can fall back on a Friedman test [12], with which we can also use the Holm-Bonferroni method for post-hoc analysis. In both cases, a significance level of $\alpha = 0.05$ is used.

5.9.2 Avatar Embodiment

During the study, we frequently observed a problem with our embodiment questionnaire as some questions were perceived as "strange" or "unclear" by the participants. For this reason, a part of our team, which had not yet dealt with the analysis and had not seen any intermediate results, re-examined each question for its validity. It became apparent that not all questions made sense in the context of our study. For this reason, we have created a shortened version of the embodiment questionnaire and removed the following questions (all 15 original questions can be seen in Figure 3.2):

1. It felt as if the virtual <u>right hand</u> I saw was some one else's.
   $\rightarrow$ Participants were confused as to whom "someone else" referred to since there was only one character in the VE.
2. It seemed as if I might have more than one <u>right hand</u>.
   $\rightarrow$ This question also caused confusion because visually only one right hand was presented.
3. I felt as if the virtual <u>right hand</u> I saw when looking at myself in the mirror belonged to another person.
   $\rightarrow$ Again, participants were confused as to whom the other person referred to.
4. I felt out of my body.
   $\rightarrow$ With this question participants often had to inquire what exactly was meant, which led to different interpretations.
5. It felt as if my real <u>right hand</u> was turning into an avatar <u>hand</u>.
   $\rightarrow$ Participants interpreted this question in very different ways.
6. I felt like I was wearing different clothes from when I came to the laboratory.
   $\rightarrow$ This question was removed because three out of our four avatars were not clothed causing participants to be confused because the question did not make sense in these contexts. As an example, participant 10 wrote *"Question about clothes is weird when I don't have a body."* referring to question 15.

[24] https://www.datanovia.com/en/lessons/repeated-measures-anova-in-r/#assumptions

As a result, we will only refer to the shortened embodiment questionnaire for further evaluation. We recommend future studies to not adopt a questionnaire in its default form, but to choose every single question carefully based on the structure of the study.

General Perception of Embodiment

To determine an embodiment score, we first labelled all questions in terms of their contribution to the sense of embodiment as either positive or negative. The only question where a higher score corresponds to a negative effect on embodiment is question 6 and is therefore marked as negative. Subsequently, the answers to the positive questions were added to a total score and the answers to the negative question were subtracted. We named this score General Perception of Embodiment (GPoE) and calculated it for each participant and each condition.

For the evaluation of the GPoE-scores, we utilized one-way repeated measures ANOVA as explained in Section 5.9.1. Since all three assumptions were met, we could proceed using ANOVA. We then performed multiple pairwise paired t-tests between all four conditions. Our p-values were adjusted using the Holm-Bonferroni multiple testing correction method.

As can be seen in Figure 5.8, the GPoE-score was not statistically significantly different between the different avatars, $F(1.68, 31.99) = 3.29$, $p = 0.058$, $\eta_g^2 = 0.08$. Post-hoc analyses with a Holm-Bonferroni adjustment revealed no statistically significant differences in GPoE-scores between: Hand and Arm ($p = 0.166$), Hand and Abstract Full-Body ($p = 0.45$), Hand and Realistic Full-Body ($p = 0.188$), Arm and Abstract Full-Body ($p = 1$), Arm and Realistic Full-Body ($p = 1$), Abstract Full-Body and Realistic Full-Body ($p = 0.59$).

However, we can also see that our p-value of 0.058 only narrowly escaped significance with a delta of 0.008. As such, the results can be considered borderline-significant. Tshikuka et al. [44] argue that the absence of statistical significance is not necessarily evidence of the absence of an effect. We endorse this sentiment and will later discuss conclusions taking this into account in Chapter 6.

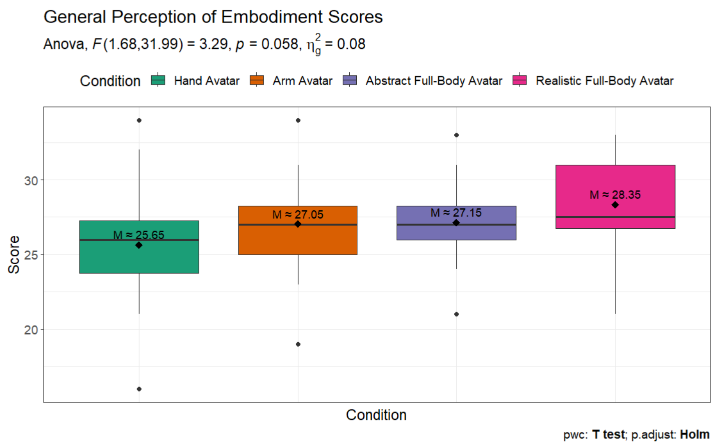
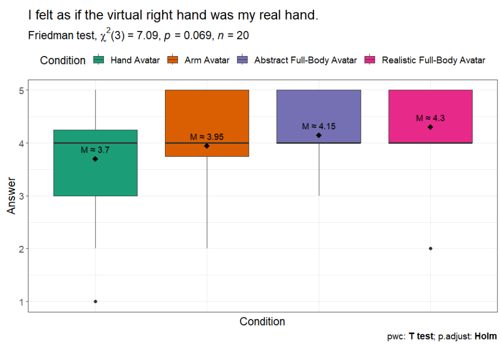
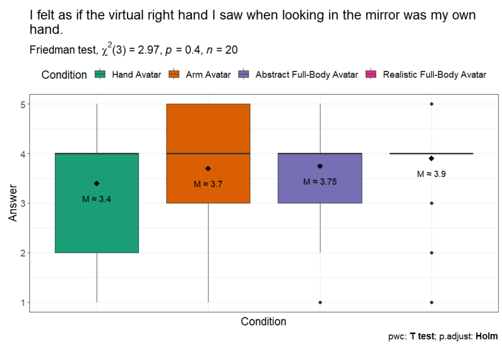


Figure 5.8: A box-plot visualising the GPoE-score results for each condition. Notice that significance was barely missed with a delta of 0.008.

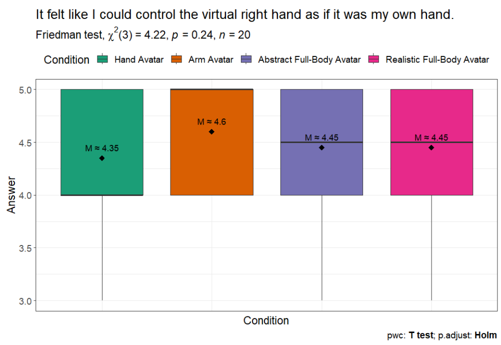
Figure 5.9 shows the box-plots of all 9 questions from the shortened embodiment questionnaire individually. The results of the excluded questions can be found in Appendix A, Figure A.0. Using the Shapiro-Wilk test ($\alpha = 0.05$) we found that the normality assumption was not met for any data set. Consequently, we used the Friedman test to examine whether there are significant differences among the four conditions. Except for question 14 (see Figure 5.9i), no plots revealed significant results.



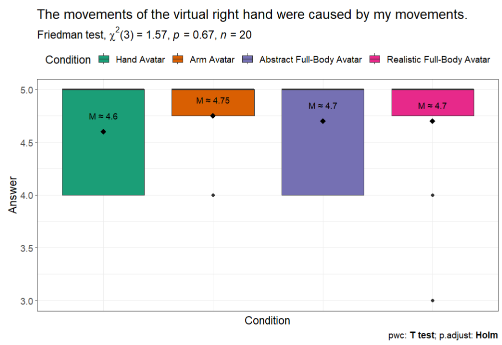
(a) Box-plot for question 1.



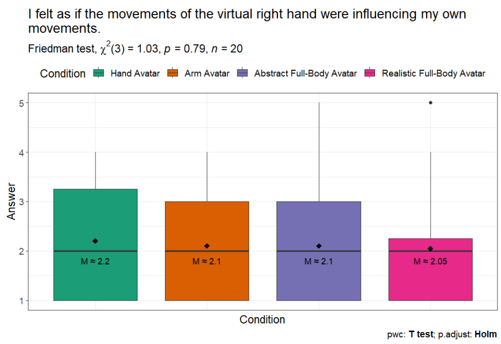
(b) Box-plot for question 4.



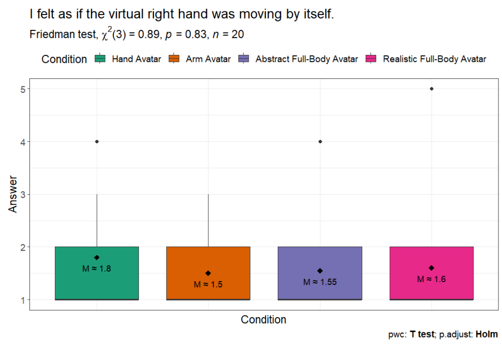
(c) Box-plot for question 6.



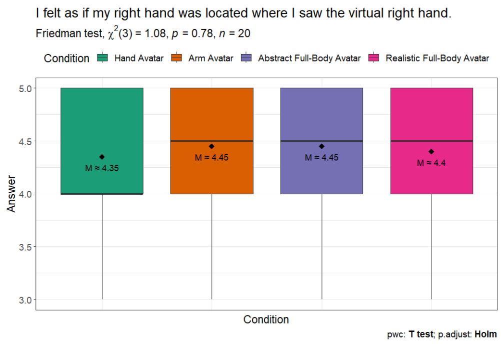
(d) Box-plot for question 7.



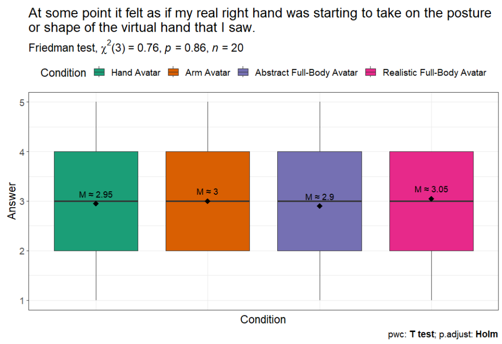
(e) Box-plot for question 8.



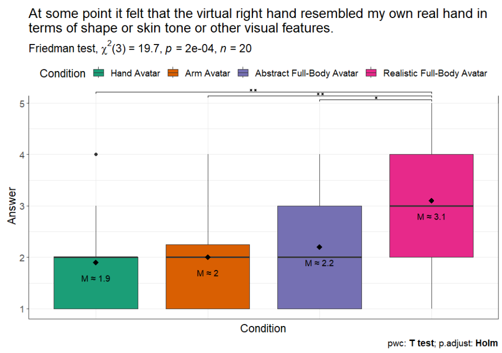
(f) Box-plot for question 9.



(g) Box-plot for question 10.



(h) Box-plot for question 13.



(i) Box-plot for question 14.

Figure 5.9: All box-plots of the questions from the shortened embodiment questionnaire

5.9.3 Hand Redirection Detection Thresholds

For the evaluation of the HRDTs, we decided to again conduct a one-way repeated measures ANOVA test. However, with this data set the normality assumption was also not fulfilled when using the Shapiro-Wilk test ($\alpha = 0.05$). This is why we opted for a Friedman test again to check whether there are significant differences between the four conditions.

As can be seen in Figure 5.10, HRDTs were not statistically significantly different between the different avatars according to a Friedman test, $\chi^2(3) = 2.89$, $p = 0.41$. Post-hoc analyses with a Holm adjustment revealed no statistically significant differences in HRDTs between: Hand and Arm ($p = 1$), Hand and Abstract Full-Body ($p = 1$), Hand and Realistic Full-Body ($p = 1$), Arm and Abstract Full-Body ($p = 1$), Arm and Realistic Full-Body ($p = 1$), Abstract Full-Body and Realistic Full-Body ($p = 0.299$). Thus, we can neither reject nor confirm **H.1**. These results will be further discussed in Chapter 6.

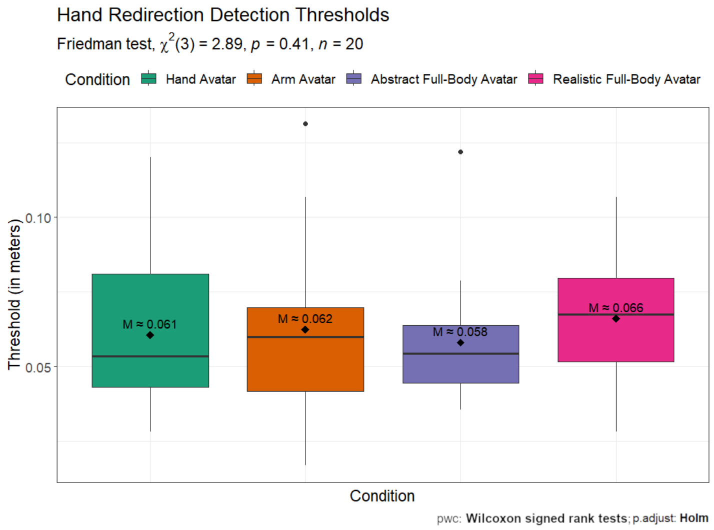


Figure 5.10: A box-plot visualising the HRDT-results for each condition.

5.9.4 Participant Feedback

The post study questionnaire gave participants the opportunity to provide their own feedback and comments about the study. Overall, we collected 11 comments which we will now list and categorize.

Three participants reported on their preferences regarding the choice of avatars:

"Arms + Hands feels way more realistic and comfortable than only hands."
- Participant 4
"I think the robot avatar works better for me than the realistic one because it's not so much in the uncanny valley, so it feels more comfortable."
- Participant 6
"'Hands only' felt the realest. 'Human' felt the weirdest, but the contrast from 'hands only' to 'full white robot body' was significant, too."
- Participant 18

Two participants described their experiences with the HR staircase procedure:

"At some time during the experiment I felt, that I intuitively corrected my hand movement based on the previous movement. I was unsure if my real hand deviated from a straight line in real life or in VR."
- Participant 1
"I thought I was redirected to the left (other direction) once."
- Participant 4

Others reported on the immersion they experienced:

"Seeing the mirrored avatar is really cool, especially with the foot tracking! Feels very real."
- Participant 6

"After the experiment I felt as if my hand was moved to the right/left when in reality it of course wasn't."
- Participant 13

Two participants mentioned that they sometimes experienced tracking problems:

"The tracking had slight issues when holding the hand near the headset."
- Participant 3
"There were some tracking issues."
- Participant 10

One participant critiqued question 15 from the embodiment questionnaire:

"Question about clothes is weird when I don't have a body."
- Participant 10

The last comment describes the participant feeling less nausea with our experiment than is usually the case in VR:

"I had less headaches and nausea than usually when I use VR. Probably because this was a very slow 'game' without any walking."
- Participant 7

5.9.5 Simulation Sickness Questionnaire

To determine whether the results could be related to cybersickness, we evaluated the SSQ results. For this, four scores were calculated: Nausea ($M \approx 10.97, SD \approx 9.92$), Oculomotor Disturbance ($M \approx 25.77, SD \approx 15.44$), Disorientation ($M \approx 21.58, SD \approx 19.41$), and the Total Simulator Sickness Score ($M \approx 22.81, SD \approx 14.81$), as introduced by Kennedy et al. [21]. Based on these findings, it can be confirmed that the results of the study cannot be attributed to the presence of simulation sickness.

Chapter 6
Discussion

As our first goal, we set out to explore how the completeness of an avatar influences the sense of embodiment. Our second (and main) goal of our research was to investigate the connection between full-body avatars and hand redirection detection thresholds (HRDTs). In Section 5.2, we formulated two hypotheses based on our research questions. We will discuss the results of our research in the following sections. Since **H.2** is based on **H.1**, we will begin with the research question of how the avatar-completeness level (ACL) influences the sense of embodiment.

6.1 Avatar Embodiment

As shown in Section 5.9.2, General Perception of Embodiment (GPoE)-scores did not differ enough to reject or accept **H.1** with an $\alpha = 0.05$ cut-off. Nevertheless, we can call this result borderline significant with $p = 0.058$ and draw several interesting conclusions from the results.

First of all, we provided empirical evidence that the raw completeness of an avatar, regardless of its graphical realism, is accompanied by a tendency towards a greater sense of embodiment. This finding supports the current trend seen in commercial virtual reality (VR) applications to gradually shift from using detached hands (ACL-1) to complete virtual bodies (ACL-3) to further increase immersion. Since realistically designed avatars evoke a higher sense of embodiment, as demonstrated by previous research [1, 9], one can combine this insight together with higher ACLs to further strengthen the sense of embodiment.

To further analyse our obtained results, we can see that the realistic full-body avatar has the biggest variation among all participants (see Figure 5.8) resulting in a comparatively tall box in the corresponding condition. This may have been caused by the fact that for some participants this avatar resembled their real appearance more than for others. Another reason for this result could be the uncanny valley effect, which states that a person's response to a human-like entity abruptly changes from empathy to revulsion as it approaches, but fails to attain a lifelike appearance [31]. For some participants the realistic full-body avatar might have already been in the uncanny valley, but for others it may not have been. This assumption is reinforced by the remark from participant 6: *"I think the robot avatar works better for me than the realistic one because it's not so much in the uncanny valley, so it feels more comfortable."* In contrast to the realistic full-body avatar, participants' impressions were much more consistent with the abstract full-body avatar, as evidenced by the quartile groups being much closer together. However, participants agreed on the fact that the shape and skin color of the virtual hand from the realistic full-body avatar was closer to real life than in the other conditions. This is evident from Figure 5.9i.

Finally, the comparatively vertical box-plot for the hand avatar can also be explained by some of the participants' comments. In this condition there seemed to be a dichotomy between participants for whom the hand avatar felt best and vice versa. For example, participant 18 stated that *"'Hands only' felt the realest. [...]"* whereas participant 4 said that *"Arms + Hands feels way more realistic and comfortable than only hands."*.

We consequently conclude that generally there is a tendency for more complete avatars to provide a stronger sense of embodiment. However, it is important to recognize that subjective feelings, as well as the current context and the task [9], also influence how one's avatar is perceived.

6.2 Hand Redirection Detection Thresholds

Since **H.1** was borderline-confirmed, we can start discussing **H.2**. As seen in Figure 5.10, **H.2** could neither be confirmed nor rejected. When looking at the tendencies of the four avatars there also seems to be no consistency regarding HRDTs. Only the realistic full-body avatar seems to show a clearer upward trend when compared to the abstract full-body avatar. These results could have occurred for several reasons.

On one hand, the stronger sense of embodiment caused by more complete avatars might actually not have any effect on HRDTs. This would mean that developers who wish to use hand redirection (HR) in their application do not need to consider the ACL of their avatars, as it does not seem to affect how HR is perceived. On the other hand, there might be an effect that we were not able to find in our study as such an effect may be much weaker than we suspected. Such an effect could be discovered by further reducing the step size of the staircase procedure to achieve higher precision HRDTs. However, this would also mean that the practical relevance of such an effect would be questionable, since our chosen step size of 1.5cm with a travel distance of 30cm was already quite small for real world use.

Perhaps, however, there might be a more pronounced effect that was not apparent due to a mutual cancellation of effects. For example, if we consider the hand avatar with ACL-1, we can not seem to estimate the position of the hand (especially the depth) very well, because there is no connection to the body and the hand floats in front of us in a disconnected way. In contrast, avatars with a higher ACL seem to enable better estimations of the hand position by giving the user a visual cue through the angled upper and lower arm. This fact is supported by a study by Feuchtner et al. [10] where participants stated that the arm is a helpful depth cue that makes navigation easier. While this property might cause HR to be harder to notice, a weaker sense of embodiment could negate this effect.

Moreover, the results obtained in the study by Ogawa et al. [33], which stated that a more realistic avatar increases HRDTs compared to an abstract avatar (using avatars belonging to ACL-1) could not be replicated in a significant way with our study.

Whereas they claim a HRDTs increase of 31.3% from an abstract avatar to a realistic one (using a hands-only avatar), we only found an increase of 13.8% (using the mean) from the abstract full-body avatar to the realistic full-body avatar. Of course, one has to be cautious about this particular comparison, as the avatars come from opposite ends of the ACL spectrum. Nevertheless, an upward trend of HRDTs can be seen for our ACL-3 avatars.

When comparing our HRDTs to the ones obtained by Zenner et al. [47], it can be seen that the mean of our thresholds is significantly higher. While they reported that the virtual hand can be unnoticeably redirected by up to 4.5° horizontally in either direction, we obtained the values 11.5° for the hand avatar, 11.7° for the arm avatar, 11° for the abstract full-body avatar and 12.4° for the realistic full-body avatars. This can be due to various reasons, but the biggest influence was probably the difference in methodology. Our staircase procedure was susceptible to the threshold values being somewhat inflated, which will later be discussed in Chapter 7. Another reason could have been the differences in avatar visualization.

Another interesting finding is that participant 13 was immersed in the application to such an extent that the visual-proprioceptive conflict persisted even after the study. After he removed the head-mounted display (HMD), it felt to him as if his hand was not where his proprioception would perceive it to be. This effect eventually cleared up after a few minutes. He noted, that *"After the experiment I felt as if my hand was moved to the right/left when in reality it of course wasn't."*

Given these findings, we can conclude that the relationship between the completeness of an avatar and the perception of HR is not yet fully understood. In a follow-up study, small but important changes could be made in order to obtain more precise results, which we will describe in more detail in the following section.

Chapter 7
Limitations of the Current Study & Future Work

After conducting our study, we came up with some possible changes that would make a potential follow-up study more precise.

First, it occurred to us that participants may not have had enough time to build up a complete sense of embodiment with each avatar. Kalckert et al. [19] suggest that the illusion of ownership takes approximately 50 seconds to emerge for the 90th percentile of participants. In our setup, however, participants only executed five forward motions before the embodiment questionnaire was shown, with some participants executing this task especially quickly. Overall, the process from receiving a new avatar to showing the embodiment questionnaire rarely took more than a minute, and for some, only a few seconds.

It is also possible that participants did not pay much attention to their avatar despite the presence of a large mirror in the centre of their views. As it turns out many participants were highly focused on their fingertip and the virtual target-sphere during forward motions. It seems like many participants paid little attention to the rest of their virtual body. This is supported by the fact that after the appearance of the embodiment questionnaire some participants asked whether they could look at their avatar in the mirror again, since they had previously paid little to no attention to it.

This problem could be solved in a follow-up study by modifying the task for accustoming a participant to each avatar. Our task, in which participants had to perform 5 forward motions without hand redirection (HR) being applied, did not explore the virtual body well. Instead, a task in which participants really focus on the virtual body is needed to build a strong sense of embodiment. For example, one could have participants assume specific poses in which they might cross their legs or stand up similar to a commercial virtual reality (VR) experience. Thus, participants would have more time to engage with their virtual avatar, allowing us to obtain a more realistic measure of embodiment. In addition, the task should be designed in a way that it always lasts at least one minute each time to ensure that the onset time for the sense of embodiment is completed [19]. To make the experience even more lifelike, a follow-up study could also experiment with tracking additional body parts, such as the knees, shoulders, and elbows, or even full hand-tracking. This could lead to more immersion, as some participants have noticed that some virtual and real body parts (e.g. the knees) are not perfectly aligned.

Choosing the staircase procedure as an adaptive method for measuring perceptual thresholds also turned out to be problematic in certain situations. During the study, one sequence was sometimes used in succession over and over again which made it difficult for participants to recognise the presence of HR. For example, if the ascending sequence is used many times in a row, the HR-strength slowly increases over time. A participant may not notice HR until much later than usual due to the slowly increasing HR-strength, in some cases even when the strength of the stimulus is slowly approaching the maximum of 15 centimetres. This can happen as a result of the participant's real hand repeatedly adjusting to the previous trial with a slightly lower HR-strength, which can lead to a loss of reference to the baseline where no HR is being applied.

This was the case with a participant who could usually perceive a HR with a strength of more than 9cm, but ended up in a long ascending sequence between trials 16 and 20 in which he did not perceive the presence of HR until the maximum of 15cm was reached (see Figure 7.1).

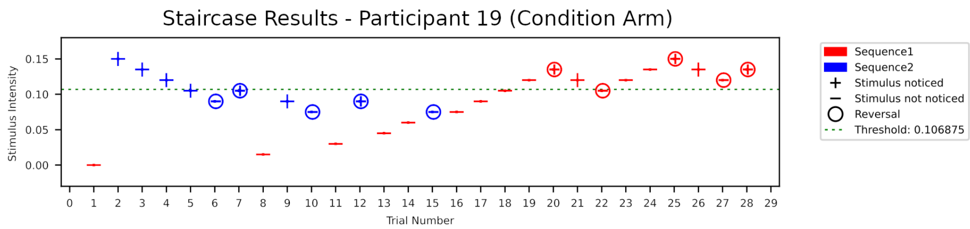


Figure 7.1: Participant 19 struggled to perceive HR in the long ascending sequence between trial 16 and 20. It was only at the maximum stimulus of 15cm, which he usually found very easy to detect, that he identified the presence of HR.

Likewise, Participant 1 wrote the following in the post-study questionnaire: *"At some time during the experiment I felt, that I intuitively corrected my hand movement based on the previous movement. I was unsure if my real hand deviated from a straight line in real life or in VR."*

As a more suitable alternative to the staircase procedure, a two-interval forced choice (2-IFC) procedure could be used in a future study [34], which could solve this specific problem. Using a 2-IFC task, participants would be given two stimuli in succession before having to answer a question. One of the two stimuli would always remain as the baseline (i.e., no HR), the other stimuli would be taken from the staircase procedure as usual. Which of the two stimuli would become the baseline is randomized. The wording of the question would then be simplified to "Did both movements feel the same?". If the answer was "No", the presence of HR was detected, whereas a "Yes" would mean that HR was not detected. Since the baseline is now included as a reference point in each trial, it is less likely for a participant to fail detecting the presence of HR due to a continuously increasing sequence. It is also important to note that due to these reasons, the threshold values would likely turn out to be lower using such a methodology. In addition, one should also reduce the step size in order to be able to find potentially smaller effects.

Furthermore, the questions of our embodiment questionnaire were not formulated in the best possible way. Since we filled in the gaps exclusively with the word "hand", the focus was not on the whole virtual body, as it should be, but on the hands instead. This can be solved in future work by reformulating the questions. To give an example, instead of "I felt as if my virtual right hand was my real hand", the formulation "I felt as if my virtual body was my real body" would have been much more appropriate, since now the question clearly refers to the entire virtual body and no longer just the hands. Another problem with the embodiment questionnaire was that we made a mistake regarding the scales. Instead of the intended 7-point Likert scale, we applied a 5-point Likert scale to the questionnaire. Of course, this does not produce false results, but the higher level of detail in the answers could have caused the differences in the General Perception of Embodiment (GPoE)-score to be significant instead of borderline-significant.

Overall, our VR setup was very robust. Only two participants stated that they experienced tracking issues, as can be seen in Section 5.9.4. Although tracking problems occurred only in rare circumstances, they still proved to be problematic when they eventually happened, as they confused participants about identifying HR. They were not sure whether HR was present, or a tracking error occurred. This was somewhat mitigated by us pointing out to participants that jumpy and abrupt hand movements are due to tracking issues and do not represent HR. In the future, this can be avoided by using additional base stations or a more stable VR system.

Chapter 8
Conclusion

Hand redirection (HR) allows virtual hand movements in virtual reality (VR) to be diverted from the real hand movement. However, if the discrepancy between the real and virtual hand becomes too great, a user may become aware of the remapping. This threshold, at which a user notices the presence of hand redirection, is called hand redirection detection threshold (HRDT). We investigated these HRDTs in conjunction with the virtual representation of a person in VR, the so-called avatar, which can take a variety of shapes and forms. We defined three avatar-completeness levels (ACLs), that indicate how fully the real body is represented in VR.

First, we hypothesized that a higher completeness of an avatar is associated with a higher sense of embodiment. Furthermore, we hypothesized that a higher sense of embodiment caused by an increased ACL would hamper the ability to detect the presence of HR. To investigate this, we conducted an experiment in which each participant repeatedly reached forward with the right hand to assess, whether hand redirection was being applied or not. This procedure was conducted using four different avatars based on three completeness levels. Using a two-sequenced staircase procedure, we derived hand redirection detection thresholds for each participant and each of the four avatars. The scenarios were very conservative, as it was ensured before the experiment that each participant knew exactly what hand redirection was and how to recognize it. No information was withheld from the participants and they were able to focus completely on detecting hand redirection during the experiment.

We provided empirical evidence for higher ACLs (independent of graphical realism) having a tendency to be associated with a stronger sense of embodiment. However, it is important to state that this is merely a tendency and the results, even if only by a small margin, were not significant. Furthermore, contrary to our hypothesis, we observed that HRDTs do not seem to get higher as the sense of embodiment gets greater caused by increased ACLs. Only the transition from an abstract full-body avatar to a realistic full-body avatar showed a tendency towards higher HRDTs.

Many publications have shown that the appearance of avatars influences a VR experience in different ways [1, 9, 15, 22, 27, 33]. In this thesis, we have shown how the completeness of avatars affects HRDTs and the sense of embodiment. Our findings suggest that developers and researchers must consider the completeness of avatars when designing VR experiences. Finally, we recommended how future work could re-examine the relationship between ACLs and the sense of embodiment, perhaps confirming that the borderline-significance shown here might indeed be significant after all.

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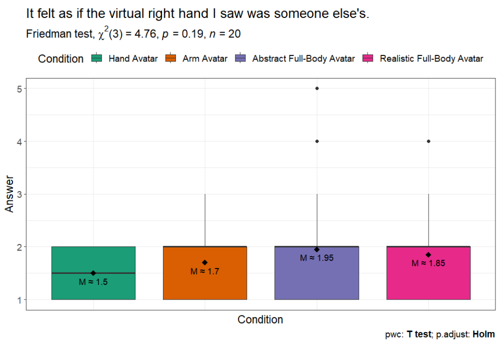
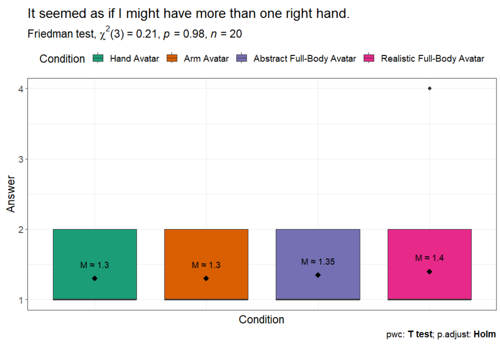
Appendix A
Embodiment Results

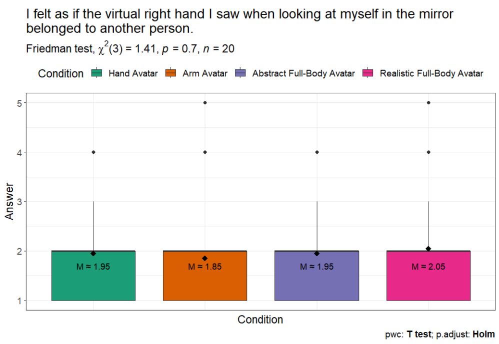
Below are the results of the questions that were removed from the original embodiment questionnaire as described in Section 5.9.2.



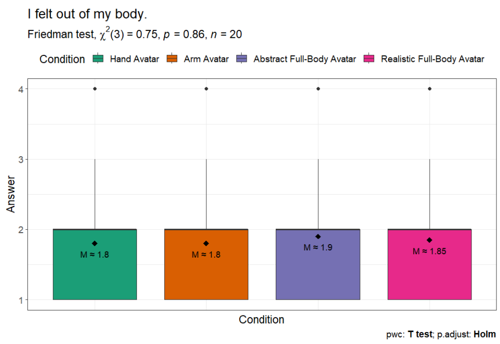
(a) Box-plot for question 2.



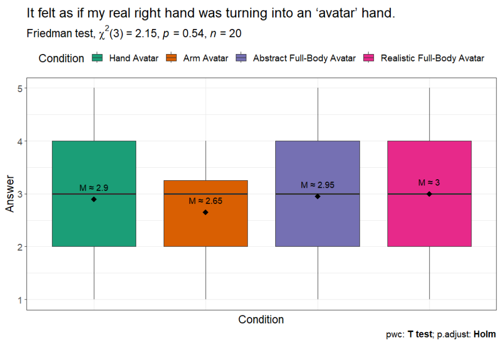
(b) Box-plot for question 3.



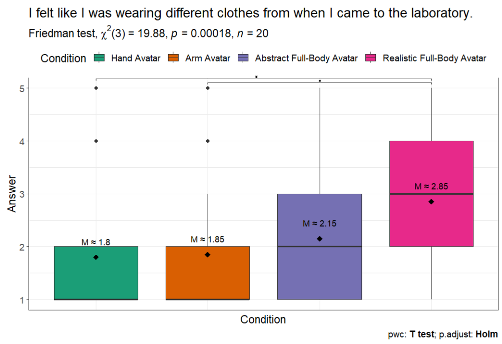
(c) Box-plot for question 5.



(d) Box-plot for question 11.



(e) Box-plot for question 12.



(f) Box-plot for question 15.

Figure A.0: All box-plots of the removed embodiment questions (reasoning in Section 5.9.2).

Appendix B
Post-Study Questionnaire

The following pages show the post-study questionnaire that was answered by the participants after the virtual reality (VR) study.

Full-Body Avatar Hand Redirection Detection Thresholds

*Required

1. Participant# (for experimenter use) *

2. Gender *

   Mark only one oval.

   - Male
   - Female
   - Non-binary
   - Other
   - Prefer not to say

3. Age *

4. Professional Background/Major (e.g. computer science, biology, chemistry) *

5. I have *

   Mark only one oval.

   - Normal vision
   - Corrected to normal vision (e.g., glasses, contacts)
   - Visual impairment

6. Do you currently experience any health issues, which might impair your vision/perception? *

Mark only one oval.

- Yes
- No

7. If so, please specify

____

8. Do you currently experience any health issues, which might impair your proprioception? *

Mark only one oval.

- Yes
- No

9. If so, please specify

____

10. Prior experience with VR? (devices such as HTC VIVE, Oculus Quest, Playstation VR) *

Mark only one oval.

- no experience – I have never used it or don't recall
- sometimes or infrequently - I use it 1 to 5 times a year
- often – I use it 6 - 10 times a year
- regular basis – I use it more than 10 times a year

11. Please briefly describe which systems you have used, and for what?

12. Prior experience with virtual 3D object interaction (e.g., games, design programs, CAD, Unity3D etc.) *

Mark only one oval.

- no experience – I have never used it or don't recall
- sometimes or infrequently - I use it 1 to 5 times a year
- often – I use it 6 - 10 times a year
- regular basis - I use it more than 10 times a year

13. Please briefly describe which systems you have used, and for what?

14. Prior experience with gaming in VR? *

Mark only one oval.

- no experience – I have never done it or don't recall
- sometimes or infrequently - I do it 1 to 5 times a year
- often – I do it 6 - 10 times a year
- regular basis - I do it more than 10 times a year

15. Please briefly describe which games you have played.

16. Do you have additional comments about the study? (optional)

Appendix C
Simulation Sickness Questionnaire

Select how much each of the following symptoms is affecting you right now on a 4-point-scale (None $\rightarrow$ Slight $\rightarrow$ Moderate $\rightarrow$ Severe).

1. General discomfort
2. Fatigue
3. Headache
4. Eye strain
5. Difficulty focusing
6. Salivation increasing
7. Sweating
8. Nausea
9. Difficulty concentrating
10. Fullness of the Head
11. Blurred vision
12. Dizziness with eyes open
13. Dizziness with eyes closed
14. Vertigo (experienced as loss of orientation with respect to vertical upright)
15. Stomach awareness (feeling of discomfort which is just short of nausea)
16. Burping

Appendix D
Study Participant Information Sheet

The following pages show the information sheet that was handed out to all participants during the briefing.

Participant Information Sheet

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study: Full-Body Avatar Hand Redirection Detection Thresholds
Department: Saarland University and DFKI (UMTL)
Name and Contact Details of the Researcher(s):

Martin Feick
DFKI Saarbrücken. Saarland University (UMTL)
Campus D3 2, 66123 Saarbrücken
Email: martin.feick@dfki.de

André Zenner
DFKI Saarbrücken. Saarland University (UMTL)
Campus D3 2, 66123 Saarbrücken
Email: andre.zenner@dfki.de

Simon Seibert
DFKI Saarbrücken. Saarland University
Campus D3 2, 66123 Saarbrücken
Email: s8siseib@stud.uni-saarland.de

Prof. Dr. Antonio Krüger
DFKI Saarbrücken. Saarland University (UMTL)
Campus D3 2, 66123 Saarbrücken
Email: antonio.krueger@dfki.de

Name and Contact Details of the Principal Researcher:

Prof. Dr. Antonio Krüger
DFKI Saarbrücken. Saarland University
Campus D3 2, 66123 Saarbrücken
Email: antonio.krueger@dfki.de

1. **Invitation Paragraph**
   You are invited to participate in a research study that serves to find out how the appearance of a virtual avatar affects the ability to notice if virtual hand movements deviate from real ones. This research supports the understanding of how far virtual hand movements can deviate in order to provide a compelling VR experience. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

2. **What is the project's purpose?**
   The project aims helping us to understand how people respond to discrepancies between the virtual and the real word while doing pointing gestures using different avatars. Your participation will approximately take 90 minutes.

3. **Why have I been chosen?**
   Participants are chosen randomly; however, we look for a diverse group of participants.

4. **Do I have to take part?**
   It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep (and be asked to sign a consent form). You can withdraw at any time without giving a reason and without it affecting any benefits that you are entitled to. If you decide to withdraw you will be asked what you wish to happen to the data you have provided up that point.

5. **What will happen to me if I take part?**
   In the first part of the experiment, you will be asked to fill in a questionnaire. We then move on to the actual experiment which will be in Virtual Reality.

   First, we will ask for your consent to measure your height, upper-arm-length, lower-arm-length and hand-length in order to calibrate the virtual avatar. These measurements will not be saved. After that we will ask you to take off your shoes and slip into special sandals with attached virtual reality trackers. We will then ask you to put a finger splint on your index finger, which also has a virtual reality tracker attached. The finger splint is used to fixate your index finger and to remove possible strain on your index finger. Then we will ask you to repeatedly place your index finger into a certain area. You will repeat this procedure multiple times. In between, you will fill in questionnaires, so that we better understand your experience. You are only required to come in once.

6. **Will I be recorded and how will the recorded media be used?**
   There are no audio and video recordings.

7. **What are the possible disadvantages and risks of taking part in the experiment?**
   Due to the use of virtual reality, there is a risk of experiencing motion sickness. Otherwise, there are no known risks involved in this procedure.

8. **What are the possible benefits of taking part?**
   Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will help us developing technology that support our understanding of perception in VR.

9. **What if something goes wrong?**
   In case you wish to make a complain about the study please contact:

   Prof. Dr. Antonio Krüger
   DFKI Saarbrücken. COS and Saarland University (UMTL)
   Campus D3 2, 66123 Saarbrücken
   Email: antonio.krueger@dfki.de

   However, if you still feel your complaint has not been handled to your satisfaction, you can contact the Chair of the Saarland University Research Ethics Committee – erb-submission@milaman.cs.uni-saarland.de

10. **Will my taking part in this project be kept confidential?**
    All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any ensuing reports or publications.

11. Limits to confidentiality

- Please note that assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.
- Please note that confidentiality will be maintained as far as it is possible, unless during our conversation I hear anything which makes me worried that someone might be in danger of harm, I might have to inform relevant agencies of this.
- Confidentiality will be respected subject to legal constraints and professional guidelines.
- Confidentiality will be respected unless there are compelling and legitimate reasons for this to be breached. If this was the case, we would inform you of any decisions that might limit your confidentiality.
- Confidentiality may be limited and conditional and the researcher has a duty of care to report to the relevant authorities possible harm/danger to the participant or others.

12. Use of Deception

Research designs often require that the full intent of the study not be explained prior to participation. This will not be the case in this study. You are/will be informed about the whole nature of the study.

13. What will happen to the results of the research project?

Collected data and results can be published or further processed in anonymous form for Bachelor and Master theses, doctoral studies, scientific publications, reports, teaching, presentations and lectures as well as for other scientific research purposes.

14. Data Protection Privacy Notice

Your personal data will be processed for the purposes outlined in this notice.

The legal basis that would be used to process your personal data will be your consent/performance of a task in the public interest.

Your personal data will be processed so long as it is required for the research project. If we are able to anonymise or pseudonymise the personal data you provide we will undertake this, and will endeavour to minimise the processing of personal data wherever possible.

15. Who is organising and funding the research?

Saarland University & DFKI

16. Contact for further information

Simon Seibert
DFKI Saarbrücken. Saarland University (UMTL)
Campus D3 2, 66123 Saarbrücken
Email: s8siseib@stud.uni-saarland.de

Thank you for reading this information sheet and for considering taking part in this research study.

Appendix E
Study Consent Sheet

The following pages show the consent sheet that was handed out and signed by all participants during the briefing.

CONSENT FORM FOR ADULTS IN RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study: Full-Body Avatar Hand Redirection Detection Thresholds
Department: Saarland University and DFKI (UMTL)

Name and Contact Details of the Researcher(s):
Martin Feick
DFKI Saarbrücken. Saarland University (UMTL)
Campus D3 2, 66123 Saarbrücken
Email: martin.feick@dfki.de

André Zenner
DFKI Saarbrücken. Saarland University (UMTL)
Campus D3 2, 66123 Saarbrücken
Email: andre.zenner@dfki.de

Simon Seibert
DFKI Saarbrücken. Saarland University
Campus D3 2, 66123 Saarbrücken
Email: s8siseib@stud.uni-saarland.de

Prof. Dr. Antonio Krüger
DFKI Saarbrücken. Saarland University (UMTL)
Campus D3 2, 66123 Saarbrücken
Email: antonio.krueger@dfki.de

Name and Contact Details of the Principal Researcher:
Prof. Dr. Antonio Krüger
DFKI Saarbrücken. Saarland University
Campus D3 2, 66123 Saarbrücken
Email: antonio.krueger@dfki.de

Thank you for considering taking part in this research. The person organizing the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

I confirm that I understand that by ticking/initialing each box below I am consenting to this element of the study. I understand that it will be assumed that unticked/initialed boxes means that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

1.	*I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction. <u>main activity:</u> Virtual Reality task Questionnaires	
2.	*I consent to participate in the study. I understand that my personal information, demographics and questionnaires will be used for the purposes explained to me. I understand that according to data protection legislation, 'public task' will be the lawful basis for processing.	
3.	**Use of the information for this project only** *I understand that all personal information will remain confidential and that all efforts will be made to ensure I cannot be identified. I request that my comments are presented anonymously with no mention of my role/affiliation.	
4.	*I understand that my information may be subject to review by responsible individuals from the University for monitoring and audit purposes.	
5.	I understand the potential risks of participating and the support that will be available to me should I become distressed during the course of the research.	
6.	I understand the direct/indirect benefits of participating.	
7.	I understand that the data will not be made available to any commercial organizations but is solely the responsibility of the researcher(s) undertaking this study.	
8.	I understand that I will not benefit financially from this study or from any possible outcome it may result in in the future.	
9.	I agree that my research data may be used by others for future research. [No one will be able to identify you when this data is shared.]	
10.	I consent to my head movements, hand movements, reach times, questionnaire answers, trial answers being recorded and understand that the recordings will be stored anonymously and will be used for research purposes. I can request the deletion/destruction of my data at any time.	
11.	I am aware of who I should contact if I wish to lodge a complaint.	
12.	Use of information for this project and beyond I would be happy for the data I provide to be archived on a secured server. I understand that other authenticated researchers will have access to my data.	

I hereby voluntarily agree to participate in the study.

I have read and understood the declaration of consent. The course of the study was explained to me orally. I have been made aware that participation can be revoked at any time by either party without giving reasons and that the execution of the study can be discontinued without any disadvantages for me.

I have not had any illness symptoms including fever, trouble with breathing, sore throat etc. in the last two weeks.

I have not visited any region which is declared as COVID-19 risk region.

I feel healthy and capable of participating in this experiment.

I have read the information on data protection and agree with it.

_______________	________________	___________________
Name of participant	Date	Signature
_________________________	________________	___________________
Researcher	Date	Signature

Appendix F
Ethical Review Board Approval

The following page shows the approval for our study by the ethical review board of the faculty of Mathematics and Computer Science at Saarland University.

Prof. Vera Demberg · Univ. des Saarlandes · Campus C 7 2

UNIVERSITÄT
DES
SAARLANDES

Prof. Dr. Vera Demberg
Member of the
Ethical Review Board
Department of Computer Sciences

Universität des Saarlandes
Saarland Informatics Campus C 7 2
D-66123 Saarbrücken
Deutschland

Fon: +49 (0) 681 302 70024
Mail: vera@coli.uni-saarland.de

Saarbrücken, 02.12.2022

Statement of the Ethical Review Board (ERB)
in response to your application (No. 22-10-5)

Dear Simon Seibert,

the ERB has reviewed your research project “Full-Body Avatar Hand Redirection Thresholds (FBAHRDT)". According to its regulations, approved by the Department of Computer Science of Saarland University on October 26, 2016, the ERB has come to the following conclusion:

“There are no ethical concerns against the implementation of these research projects.”

If you have any questions, please let me know. We wish you all the best in your future research endeavours.

Best regards, on behalf of the ERB

Prof. Dr. Vera Demberg
Member of the Ethical Review Board
of the Department of Computer Sciences at Saarland University