Understanding the Effects of Perceived Avatar Appearance on Latency Sensitivity in Full-Body Motion-Tracked Virtual Reality

David Halbhuber
david.halbhuber@ur.de
University of Regensburg
Regensburg, Germany

Martin Kocur
martin.kocur@fh-hagenberg.at
University of Applied Sciences Upper Austria
Hagenberg, Austria

Alexander Kalus
alexander.kalus@ur.de
University of Regensburg
Regensburg, Germany

Kevin Angermeyer
kevin.angermeyer@stud.uni-regensburg.de
University of Regensburg
Regensburg, Germany

Valentin Schwind
valentin.schwind@acm.org
Frankfurt University of Applied Sciences
Frankfurt, Germany

Niels Henze
niels.henze@ur.de
University of Regensburg
Regensburg, Germany

ABSTRACT

Latency in virtual reality (VR) can decrease the feeling of presence and body ownership. How users perceive latency, however, is malleable and affected by the design of the virtual content. Previous work found that an avatar's visual appearance, particularly its perceived fitness, can be leveraged to change user perception and behavior. Moreover, previous work investigating non-VR video games also demonstrated that controlling avatars that visually conform to users' expectations associated with the avatars' perceived characteristics increases the users' latency tolerance. However, it is currently unknown if the avatar's visual appearance can be used to modulate the users' latency sensitivity in full-body motion-tracked VR. Therefore, we conducted two studies to investigate if the avatars' appearance can be used to decrease the negative impact of latency. In the first study, 41 participants systematically determined two sets of avatars whose visual appearance is perceived to be more or less fit in two physically challenging tasks. In a second study (N = 16), we tested the two previously determined avatars (perceived to be more fit vs. perceived to be less fit) in the two tasks using VR with two levels of controlled latency (system vs. high). We found that embodying an avatar perceived as more fit significantly increases the participants' physical performance, body ownership, presence, and intrinsic motivation. While we show that latency negatively affects performance, our results also suggest that the avatar's visual appearance does not alter the effects of latency in VR.

KEYWORDS

Latency, Virtual Reality, Latency Compensation, Proteus Effect

ACM Reference Format:
David Halbhuber, Martin Kocur, Alexander Kalus, Kevin Angermeyer, Valentin Schwind, and Niels Henze. 2023. Understanding the Effects of Perceived Avatar Appearance on Latency Sensitivity in Full-Body Motion-Tracked Virtual Reality. In *Mensch und Computer 2023 (MuC '23), September 03–06, 2023, Rapperswil, Switzerland.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3603555.3603580

MuC '23, September 03–06, 2023, Rapperswil, Switzerland

ACM ISBN 979-8-4007-0771-1/23/09.
https://doi.org/10.1145/3603555.3603580

1 INTRODUCTION

Virtual Reality (VR) allows users to dive into virtual worlds, engage, collaborate with others, or experience games and applications in an immersive manner. Typically, users wear head-mounted displays (HMDs) to interact with the virtual world, which can be coupled with full-body motion tracking (MT) to increase immersion. MT systems mirror the user's body movement in VR, enabling high levels of presence and illusion of body ownership [20, 58]. However, full-body MT is computationally expensive since a range of cameras has to continuously detect, track, process, and pass on information about multiple reflective markers worn by the user to a central processing unit. Specialized software can reconstruct and translate the user's pose to the virtual world using the provided marker information. This extensive processing pipeline increases the system's latency. High latency in VR adversely affects users' experience and performance [19]. Temporal asynchronicity between the user's actual movement and the displayed movement in the HMD leads to a reduced feeling of presence [47], a reduced illusion of body ownership [31] and an increased level of VR motion sickness [58]. Besides latency, the avatar—the user's digital representation in VR—profoundly shapes how users experience and interact with the virtual world. The embodiment of an avatar triggers a top-down process that changes users' behavior, attitude, and perception [35, 36, 38]. These changes are formed by previous experience, contextual cues, and biological characteristics that ultimately determine the response to an avatar. Adapting to one's expectation of an avatar is attributed to the Proteus effect [33, 66, 67]. Previous work investigating the Proteus effect, for example, showed that embodying specific avatars alters the users' physical activity in exergames [50, 51], their performance in physical tasks [35, 38] or their walking speed [53].

However, the avatar's visual appearance not only alters users' experience and behavior in a virtual environment [31, 34, 39, 47, 58] but potentially also influences the users' sensitivity to latency. In previous work, Claypool & Claypool [15] demonstrated that users playing a non-VR video game are less affected by the adverse effects of latency if they controlled a digital representation that was implicitly perceived to be slower. The authors argued that the avatar's diminished responsitivity better matched the users' expectation of how the avatar has to behave based on its visual appearance. Hence, using avatars to alter the users' expectations of the interaction could inhibit the adverse effects of latency.

Previous work shows that both the embodied avatar [6, 7, 38, 66, 67] and latency [31, 47, 58] fundamentally change how users experience and behave in VR. Moreover, previous research in non-VR video games also demonstrates that players tolerate higher latency if the controlled avatar better fits the user's mental model of the interaction [15]. However, it is currently unknown if the avatars' visual appearance in VR can be used to compensate for the adverse effects of latency. Answering this question poses two problems: Firstly, it needs to be established what type of visual appearance leads to avatars being perceived as a better fit for certain interactions. Secondly, it is also unknown if previous findings regarding the interaction between latency and the avatar in video games translate to a highly immersive full-body MT VR setting.

This work investigates how the avatar's visual appearance interacts with latency in full-body MT VR. Since previous work indicates that an avatar's appearance has a systematic effect on physical performance [34, 35, 38], we specifically explore the interplay of avatar and latency in two physically demanding tasks. The first task required quick motion and flexibility, while the second task necessitated a high level of power and force. We designed two sets of avatars (male and female) using the 3D-suite DAZ3D and the humanoid Genesis 8 avatar pre-set. We systematically altered the avatars' appearances by increasing body fat and muscularity levels to manipulate their potential suitability for the designed tasks. Using this method, we parameterized the visual appearance of 32 avatars (16 male, 16 female). Subsequently, we conducted an online survey with 41 participants to determine what avatar's visual appearance is overall perceived to be best fitting for the two tasks. After establishing four avatars (two male and two female) with contrasting levels of perceived fitness (perceived to be more fit vs. perceived to be less fit), we conducted a VR experiment. Sixteen participants completed two tasks in VR while embodying both types of avatars with two levels of latency (system and high) while assessing the participants' performance, feeling of body ownership, presence, enjoyment, perceived exertion, and heart rate.

Our analysis revealed no interaction between the avatar's visual appearance and latency. However, we found that participating with the avatar perceived as more fit increases participants' physical performance, feeling of body ownership, agency, experienced realism, and competence. Additionally, we found that latency negatively influenced the participants' scores and error rates. Our results suggest that the embodiment of different avatars does not modulate the adverse effects of latency. However, as participants performed better using the avatar perceived to be more fit, our work also replicates and extends previous findings regarding the Proteus effect in VR [7, 35, 38]. Our results indicate that the avatar's visual appearance does not manipulate the latency sensitivity of full-body MT VR settings. Nevertheless, we argue that future work should further investigate how an avatars visual characteristic, such as its clothing or accessory, can potentially be leverage to counteract the negative effects of latency. We provide all material via *Open Sciences Framework* to enable future research to build upon our work. The repository includes source codes of the used VR tasks, gathered anonymized user data, and the full statistical analysis[1].

2 RELATED WORK

In the following section, we first provide an overview of latency and its effects in VR. We continue by shedding light on previous approaches to compensate for latency and by highlighting work investigating avatars to counteract latency in non-VR video games. Next, we elucidate what effects avatars can induce in VR. We conclude this section with a summary demonstrating the relevance of studying the interaction between latency and the used avatar in full-body MT VR.

2.1 Latency in Virtual Reality

According to Battle et al. [8], latency refers to the time delay between a user's input and the corresponding reaction of the interactive system. Latency can be influenced by various factors, including the perceptual channel, which includes visual, haptic, and auditory feedback. Technically, latency can be classified as either local latency or network latency. Local latency is caused by the user's peripheral devices, such as the computer mouse, keyboard, and monitor [64]. In contrast, network latency arises from communication over a network, such as the Internet [27]. Software systems that rely on network connections, such as multiplayer games, chats, and browser-based programs, are affected by network latency. This latency significantly impacts the responsiveness of these programs, thus, affecting the gaming experience of players in non-VR video games [22–25]. Latency is also known as system response time (SRT) [3] and has been extensively researched since Miller's first latency studies in 1968 [48].

The users' interactions in full-body MT VR are affected by both types of latency (local and network). Typically, the user's raw input has to be received and processed by a local motion-capturing system and sent over a network connection to another dedicated machine responsible for rendering the processed data to the user's HMD. Regardless of its origin, latency in MT VR leads to a drift between the user's real body movement and the displayed virtual avatar movement. This mismatch between real and digital representation causes VR motion sickness or postural instability [1, 62]. Early work by Meehan et al. [47] demonstrated that increasing the input-output latency as little as 40 ms in a VR setting already induces a loss of self-reported presence. In similar work, Caserman et al. [12] investigate how the users' task performance was influenced by latency in two different tasks. The authors revealed that latency starting at 69 ms significantly and negatively impacts the users' performance. Additionally, Caserman et al. also unraveled that body ownership—the experience of one's body as one's own [13]—starts to decrease at 101 ms. Summarizing previous work on the effects of latency in VR, it is apparent that latency leads to a reduced user experience in VR.

---

[1] https://osf.io/juh8k/?view_only=7c9c07320cff43a699dedc6bc035289c

2.2 Compensating for Latency

Previous work offers numerous approaches to compensate for the negative effects induced by latency [46]. However, most of the previous works focus not on full-body tracked VR but on traditional non-VR video games. Gutwin et al. [21], for example, proposed a method to reveal the latency of a gaming environment to its users. In their work, the authors used specialized game objects to indicate the level of latency in the gaming session. This approach allows the users to adapt to latency, increasing the user experience. Other work, such as by Halbhuber et al. [22, 26], uses artificial neural networks (ANNs) for latency compensation in video games. These ANNs use information about the user's previous movements and actions to predict what they will do next. The game, in turn, can start processing the following action before the user has performed it. Ultimately, this predictive game loop reduces the user-perceived latency, increasing gaming experience and player performance. Schwind et al. [58] used a similar approach to predict avatar movement in a full-body MT VR setting. Although the authors were able to reduce the adverse effects of latency on the user experience, their algorithms could not alleviate user performance to a low-latency level.

There are different other approaches to compensate for latency in video games, such as *Time Warp* [10, 30], *Geometrical Manipulation* [42], or *World Adjustment* [46]. These approaches, however, mostly focus on manipulating the game world or on predicting user inputs. They do not account for the user's digital representation. One exception is the work presented by Claypool & Claypool [15], in which the authors demonstrated that playing with a larger avatar leads to a higher latency tolerance. The authors argue that the increased latency tolerance when playing with a larger avatar is caused by the players associating the larger avatar with inherently slower movement. Hence, the slower reaction of the avatar better matches the user's mental model of the interaction and is, thus, not as disruptive as playing with the smaller and agile avatar.

2.3 Avatar-induced Effects in Virtual Reality

Designers and researchers commonly use avatars to provide users with a virtual body and create immersive VR experiences [33, 61]. In VR, users take on digital bodies through avatars, which serve as their self-representation and interface to the digital world [4]. When users see the virtual environment from a first-person perspective—as if they see the virtual environment from the eyes of the avatar—and their movements are reflected in the avatar, they can experience visuomotor synchrony, which leads to altered sensations while embodying the avatar [37, 40, 60]. This virtual embodiment of avatars can trigger perceptual and physiological effects that are promising from an human-computer interaction perspective as they can be leveraged to build more effective and interesting VR applications [33].

When a user embodies an avatar, it can activate a process that leads to changes in behavior, attitude, and perception [67]. These changes are caused by the avatar's specific visual characteristics, which are associated with previous knowledge and experiences about characters or stereotypes [33, 52]. This phenomenon is called the Proteus effect [66]. Yee et al. [67] showed that users who embodied attractive avatars behaved more self-confidently during a VR dialogue. They walked significantly closer to their confederate in VR and provided more information about themselves. In a separate study, the authors revealed that users who embodied taller avatars negotiated more aggressively and confidently in a VR bargaining task [67]. These effects can be explained by the self-perception theory [9] that postulates that users observe and evaluate themselves from an imaginary third-person perspective to make inferences about their behavior based on typical expectations. As attractiveness and body height are commonly associated with confidence, extraversion, and self-esteem, users tend to adapt their behavior to conform to the salient visual characteristics of their avatars.

Ratan et al. [52] showed in a meta-analysis that the Proteus effect could be induced in different contexts. Reinhard et al. [53], for example, demonstrated that embodying an elderly avatar affected real-world walking speed after the VR experience. Another study showed that playing virtual tennis on a Nintendo Wii with an avatar the authors dubbed obese resulted in lower physical activity than a more athletic avatar [51]. The authors could replicate the findings in a second study [50], indicating the reliability of such effects. Hence, the avatar's perceived athleticism affected how users played the game and caused them to adjust their physical effort in concordance with the affiliated associations. In this vein, Kocur et al. [35] also revealed that participants had a lower perception of effort while cycling in VR when they embodied an athletic avatar compared to a non-athletic version. Interestingly, the authors could show systematic effects on the heart rate, indicating the psychophysiological impact of an avatar's appearance. Further studies showed that muscular avatars increased grip strength [38], sweaty avatars increased perceived exertion [34] , and elderly avatars affected physical performance [43].

On the contrary, Lin et al. [44] showed that avatars with pronounced abdominal muscles reduced physical activity instead of boosting performance. This is in line with Koulouris et al. [41], who showed that idealized avatars can negatively affect cycling performance. Although there is a strong tendency towards consistent effects of avatars' appearance and their connected associations [52], some studies could not reproduce the effects as expected [43, 44]. Hence, more research is required to learn about the utilization of avatars' effects with the goal of creating more effective VR applications.

2.4 Summary and Research Question

Previous work shows that an avatar's visual appearance in VR can trigger a top-down effect that alters the users' behavior, attitude, and perception called Proteus effect [33, 66, 67]. However, virtual environments are affected by latency, which decreases user experience and performance [1, 47, 58]. Previous work investigated how the avatar's visual appearance in non-VR gaming settings varies the effects of latency [15] and shows that an avatar that better matches the user's mental model of the interaction decreases the adverse effects of latency. However, whether those findings translate to a highly immersive full-body MT VR setting potentially influenced and formed by the Proteus effect is yet to be answered. Thus, it is also unknown whether the avatar's visual appearance can be leveraged to increase the users' latency tolerance and decrease the negative effects of latency in a full-body MT VR environment. Building on this, we formulate our research question as follows:

- RQ_1 *"Does an avatar that better matches the user's mental model of an interaction increase performance and experience in full-body motion-tracked virtual reality?"*
- RQ_2**":** *"Can an avatar's that better matches the user's mental model of an interaction be leveraged to alter the latency tolerance of full-body motion-tracked virtual reality?"*

3 DETERMINING AVATARS' VISUAL APPEARANCES

To investigate how avatars' visual appearances can be manipulated to enhance perceived fitness for specific tasks, we developed two physically challenging tasks. These tasks were designed based on previous work that demonstrated that the visual appearance of avatars has a systematic impact on physical performance [34, 35, 38]. We developed two different tasks to depict a broader range of physical demands and differing levels of athleticism requirements. In the first task—the reaction wall task— potential participants stand in front of a virtual wall divided into 32 fields in an 8 × 4 grid. Each of the individual fields of the wall can light up. The goal of the reaction wall task is to touch the flashing field as quickly as possible. The reaction wall task requires quick motion and fast reaction times. In the second task—the barbell task— the goal is to perform two-handed bicep curls. The barbell is gripped with both hands and then lifted to the chest in a controlled motion by bending one's arms. At the same time, the elbows should not move. The entire force to bend should stem from the bicep muscles. The barbell task necessitates a high level of force and raw power.

We followed the presented procedure by Kocur et al. [35] to design different avatars. We utilized the 3D-suite DAZ3D[2] and the Genesis 8 avatar pre-set[3] to systematically alter the avatars' appearances by changing body fat and muscle mass. Each dimension (body fat and muscle mass) was independently increased in 33% steps, which results in four levels for each dimension (0%, 33%, 66%, and 100%). To prevent a bias induced by a mismatch between the participants' gender and the avatars' gender [59], we designed different avatars for males and females. Combining all possible body fat and muscle mass levels led to 16 avatar combinations per gender, resulting in a total of 32 avatars. Figure 1 depicts all 16 female (left) and all 16 male (right) avatars.

3.1 Procedure, Stimuli, and Measures

We conducted an online study to establish which visual avatar appearance participants perceive as more or less fit. Participants were provided with a hyperlink to take part in the study. After giving informed consent and receiving a brief introduction to the study's purpose, participants answered a demographic questionnaire stating their age, gender, height, weight, and course of study or occupation. Next, we asked participants to self-rate their fitness level using the Self-Perception of Fitness (SPF) scale [18]. The SPF is built by five dimensions: (1) *Endurance*, (2) *Strength*, (3) *Flexibility*, (4) *Body Composition*, and (5) *Fitness.* Participants rated their fitness level for each dimension on a 13-point scale ranging from 1 (low level of fitness in this dimension) to 13 (exceptionally well in this dimension).

After the initial questionnaires, we presented the participants with two videos showing examples of the two tasks (reaction wall and barbell task) [4][5]. We used the videos to familiarize the participants with the potential tasks (see Figure 5), allowing them to estimate what kind of avatar they believed would best fit the respective task. After familiarizing the participants with both tasks, they were presented with the first avatar rendering. Participants who identified as male were presented with male avatars, and participants who identified as female were presented with female avatars. Conditions were presented in a randomized order. Each participant was shown all 16 avatars. For each avatar, we asked the participants to imagine that they are embodying the currently depicted avatar and to estimate their performance using the SPF (*Endurance*, *Strength*, *Flexibility*, *Body Composition*, and *Fitness*). Furthermore, participants also answered task-specific questions: We asked about their expectations regarding how well they would perform using the depicted avatar in the reaction wall task operationalized as the overall performance (*Wall Performance*), the reaction time (*Wall Reaction Time*), and the time required to finish the task (*Wall Completion Time*). For the barbell task, we asked how the participants expected to perform overall (*Bicep Curl Performance*) and how much weight they could lift (*Bicep Curl Weight*). We also asked the participants how fast and agile (*Agility* and *Speed*) they thought the avatar shown was. All questions were answered on a scale from 0 % (poor) to 100 % (very good). Lastly, we also asked the participant how much the current avatar resembled themselves on a 5-point scale (*Avatar is Me* and *Avatar is Not Me*) ranging from 1 (not at all) to 5 (very much). The study, which was designed and conducted following the research ethics policy of our institution, took about 30 minutes to complete.

3.2 Participants

We recruited a total of 41 participants (26 male, 15 female) using our institution's mailing list. The participants' age ranged from 18 to 29 years with a mean age of 22.73 years (SD = 2.28 years). Using the weight and heights provided by the participants, we calculated the *Body Mass Index* (BMI), which ranged from 16.41 to 32.74 kg/m^2, with a mean BMI of 23.06 kg/m^2 (SD = 2.28 kg/m^2). Participants self-rated their level of fitness to be average. On average they reported 7.24 points (SD = 2.14 points) in *Endurance*, 7.95 points (SD = 2.36 points) in *Strength*, 7.80 points (SD = 2.62 points) in *Flexibility*, 7.54 points (SD = 2.13 points) in *Body Composition*, and 7.49 points (SD = 2.46 points) in the *Fitness* category. All participants were students at our institution and received a half credit point for their course of study.

3.3 Determined Avatars for the User Study in VR

To determine the visual appearance of the avatars used in our second study, we combined the scores of the SPF, the estimated performance for both tasks and the estimated speed and agility. We calculated the average for each measure. The visual appearance of

---

[2] https://https//www.daz3d.com

[3] https://https//www.daz3d.com/genesis8

[4] Reaction Wall: https://www.youtube.com/watch?v=jn-VAVptu_c

[5] Bicep Curl: https://www.youtube.com/watch?v=Nkl8WnH6tDU

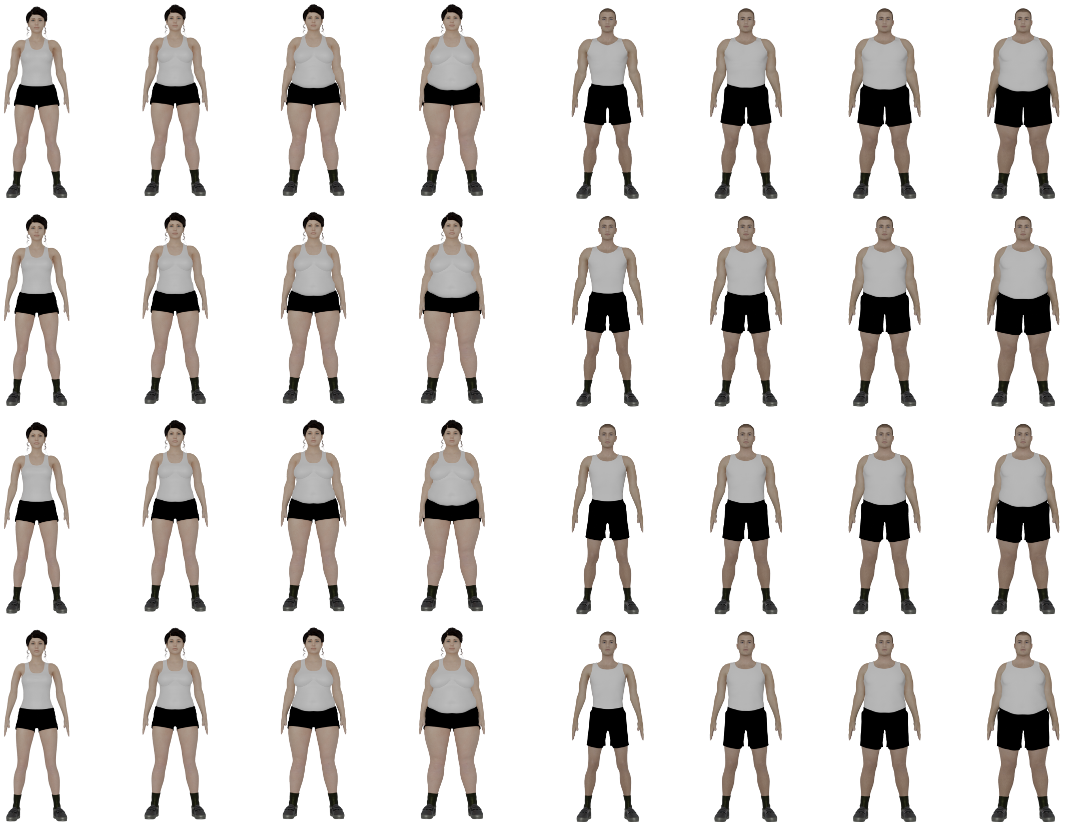

Figure 1: Female (left) and male (right) avatars used in the first study to establish when participants perceive avatars as more or less fit. To alter the avatar's appearance, we systematically altered its appearance by changing body fat and muscle mass. Each dimension (body fat and muscle mass) was independently increased in 33% steps, which results in four levels for each dimension (0%, 33%, 66%, and 100%). The bottom left avatar of each set has 0% body fat and a muscle mass of 0%. Respectively, the top right avatar of each set has 100% body fat and a muscle mass of 0%.

the *perceived as more fit* avatar was designed based on the highest scores, and vice versa, the visual appearance of the *perceived as less fit* avatar was designed based on the lowest mean score for each measure. We independently determined the *perceived as more fit* and *perceived as less fit* visual appearance for male and female avatars. The scales *Avatar is Me* and *Avatar is Not Me* were not included in the final scores, but were only used to check if the designed avatars were appropriate to our participants at all. Figure 2 and Figure 3 depict heatmaps of the given score for all tested female and male avatars.

Following this approach, the male *perceived as more fit* avatar is defined by 86.11 % muscularity and 0 % body fat, and the *perceived as less fit* avatar by 75 % muscularity and 91.66 % body fat. The female *perceived as more fit* avatar resulted in 100 % muscularity and 0 % body fat, and the *perceived as less fit* avatar in 66.6 % muscularity, and 100 % body fat. Figure 4 depicts the final male and female *perceived as more fit* and *perceived as less fit* avatars.

4 INVESTIGATING THE INTERACTION OF AVATAR'S VISUAL APPEARANCE AND LATENCY

We conducted a study to investigate how the avatar's visual appearance interacts with latency in MT-VR. Our work, hence, clarifies if an avatar's visual appearance can be used to counteract the adverse effects of latency.

4.1 Study Design

We designed a within-subjects study and used two independent variables (IVs): (1) Visual Appearance (*perceived as more fit / perceived as less fit*) and (2) Latency (*system / high*) to operationalize the avatar's visual appearance (1) and latency (2). The *system* level of Latency refers to the unaltered baseline latency of the used MT VR system, *high* refers to 100 ms of latency artificially added to the system by frame buffering. We set the *high* level of latency in line with previous work, which postulates latency between 50 ms [47] and 80 ms [2] can be tolerated by users before it starts affecting the users' experience and performance negatively. Thus, to ensure an adverse effect of latency, we increased it slightly further than the

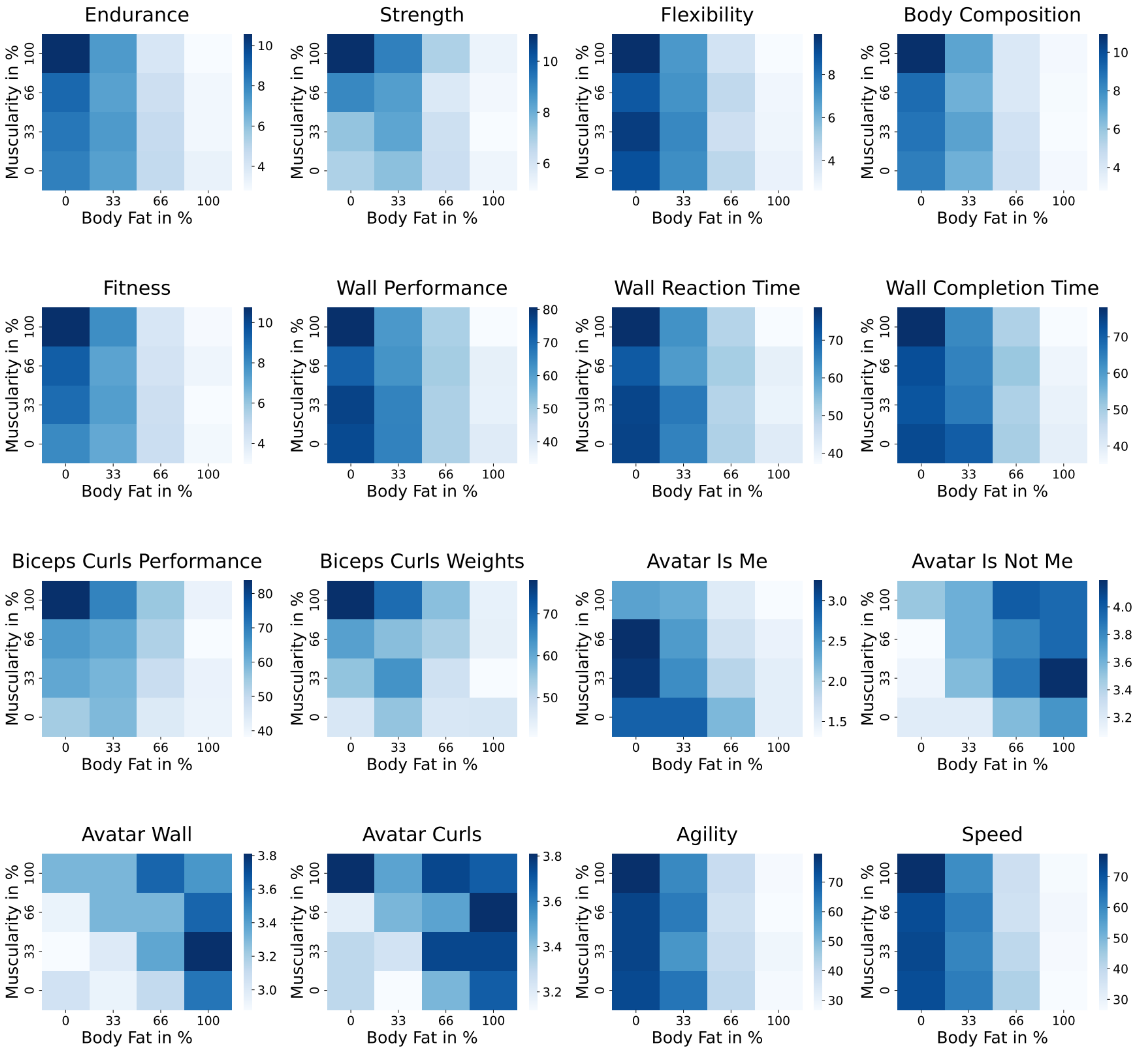

Figure 2: Heatmap depicting the mean scores of the female avatars for each question asked in the online study. Answers were either given between 0 – 100 % or on a 5-point Likert scale. A darker field corresponds to a higher score, and a lighter field depicts a lower score.

recommendation by previous work [2]. Every participant tested each combination of VISUAL APPEARANCE and LATENCY. To prevent a bias induced by gender mismatch [59], participants embodied avatars of their identified gender. Furthermore, we used a Latin Square to counterbalance conditions to prevent a sequencing effect.

4.2 Tasks

In our study, participants performed two different tasks in VR. We used two tasks in our study to reflect a more extensive range of motion and to require different levels of agility and speed from the participants. Their movement was registered and transferred onto the avatar during the VR experience to induce body ownership sensations.

In the first task—the reaction wall task— the participant aimed to touch the flashing field as quickly as possible in 60 seconds. After touching the wall, whether the participant touched the correct or the wrong field, the flashing on the field stopped, and another area started to flash. To increase the difficulty of the task, two consecutive light flashes were not allowed to either be on the same field or a field directly adjacent to the last field. If participants touched the correct field, they obtained one point. They did not lose points for touching the wrong field.

In the second task—the barbell task—participants were asked to perform two-handed bicep curls. We provided participants with a real-world barbell with a total weight of 5 kg. The barbell's position was translated to the virtual world using rigid body motion tracking. The task's goal was to execute as many bicep curls as possible in 40 seconds. We reduced the task time compared to the reaction wall task because performing bicep curls is highly exhausting. Figure

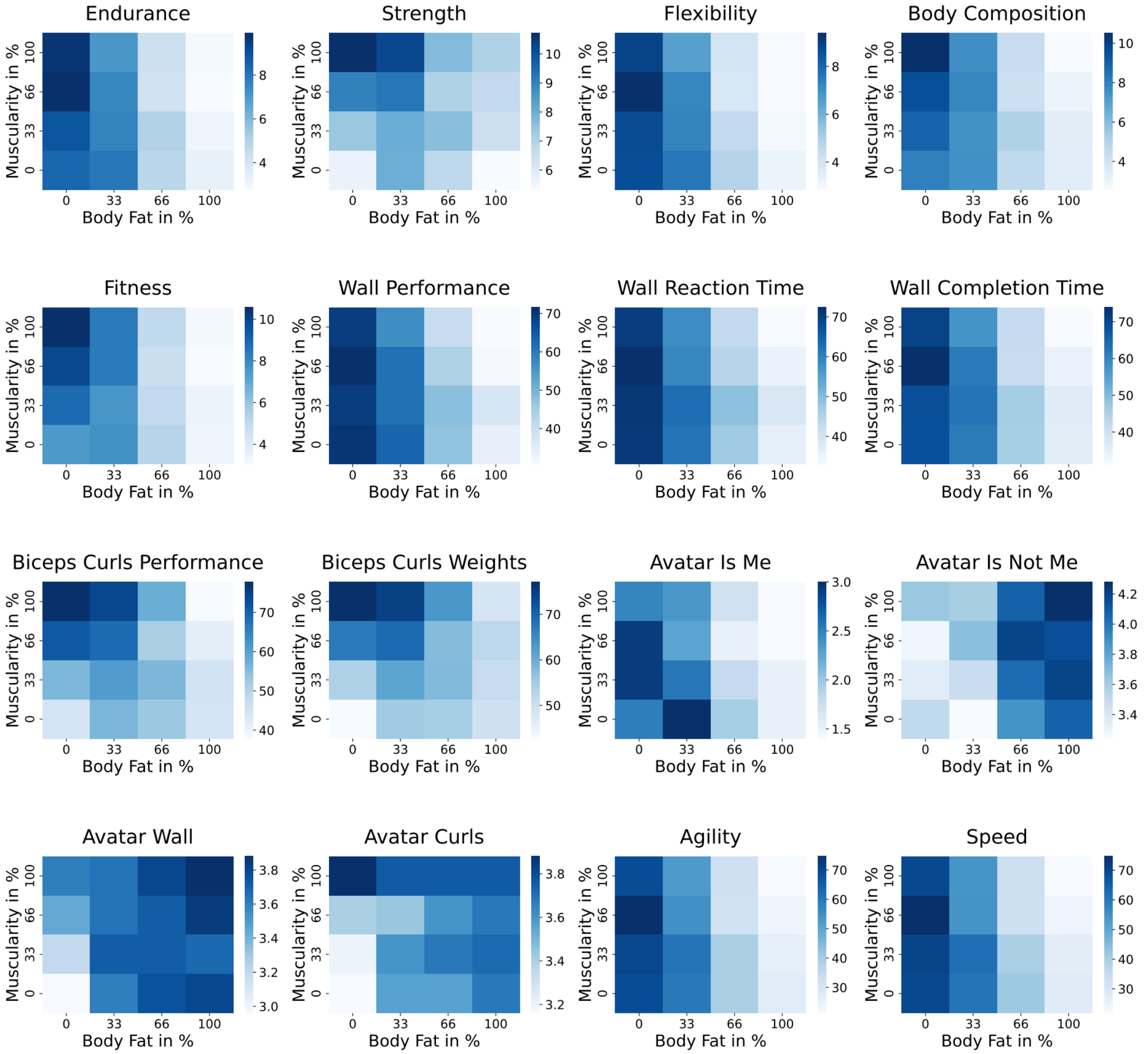

Figure 3: Heatmap depicting the mean scores of the male avatars for each question asked in the online study. Answers were either given between 0 − 100 % or on a 5-point Likert scale. A darker field corresponds to a higher score, and a lighter field depicts a lower score.

5 depicts the participants' view in the reaction wall task (left) and the barbell task (right).

To increase body ownership sensation, both tasks were performed in front of virtual mirrors. While participants were able to see the whole avatar in the barbell task in the mirrors, parts of the avatar were occluded by the reaction wall in the reaction wall task.

4.3 Measures

Building on previous work [38], we recorded a range of dependent variables (DVs), which are potentially affected by latency [1, 47, 58], to measure the participants' experience and performance. We measured the subjectively *perceived exertion* by using Borg's scale [11], since previous work demonstrated that the the avatar's visual appearance can alter the participants psychological responses [35]. While in a task, we asked participants every 20 seconds to rate their level of physical exertion on a 20-point scale from 6 (no or minimal exertion) to 20 (maximal exertion). In line with previous work [5, 7], we quantified body ownership, as a metric of the VR setting's quality, using the body representation questionnaire (BRQ) with its five subscales *vr-body*, *mirror*, *feature*, *agency* and *twobodies*. Further, we assessed the *general presence* (G1) and the *experienced realism* (REAL1, REAL2, REAL3, REAL4) by utilizing the Igroup presence questionnaire (IPQ) [57]. Additionally, we measured the *enjoyment* and the *perceived competence* of the participants by using the intrinsic motivation inventory (IMI) [54]. All instruments were administered according to previous work [5, 54, 57].

Besides the subjective measures, we also measured the participants' performance and heart rates. To assess the performance in the reaction wall task, we noted overall *score* - the number of

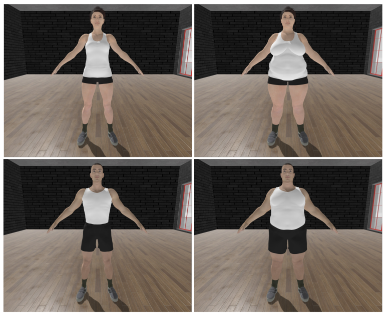

Figure 4: Avatars perceived to be *perceived as more fit*/*perceived as less fit* by participants and thus used in the second study. The male *perceived as more fit* avatar (bottom left) is defined by 86.11 % muscularity and 0 % body fat, and the *perceived as less fit* avatar (bottom right) by 75 % muscularity and 91.66 % body fat. The female *perceived as more fit* avatar (top left) resulted in 100 % muscularity and 0 % body fat, and the *perceived as less fit* avatar (top right) in 66.6 % muscularity and 100 % body fat.

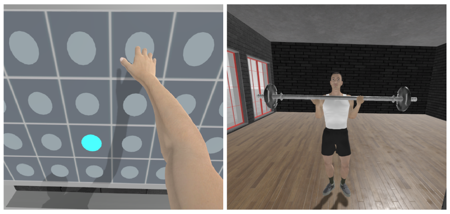

Figure 5: Participants performing our two tasks in full-body motion-tracked virtual reality while embodying the two opposing avatars designed in the first study. The left shows the reaction wall task, in which participants had to touch flashing lights as quickly as possible to obtain points. The right depicts the barbell task, in which participants had to perform as many bicep curls as possible in 40 seconds using a real 5 kg barbell, while seeing their avatar in a virtual mirror.

correctly touched fields in 60 seconds - and the *error* - the number of incorrectly touched fields in 60 seconds. To rate the participants' performance in the bicep curl task, we logged the total number of *barbell repetitions*. We measured the participants *heart rate* using a Polar OH1 sensor, to obtain an objective measure of the participants' psychological response to different levels of latency and avatar appearance.

4.4 Procedure

Participants were briefed about the procedure and purpose of the study and gave informed consent. Next, participants filled out a demographic questionnaire in which they answered questions regarding their person (age, identified gender, occupation, height, weight, SPF). After finishing the demographic questionnaire, we asked participants to self-rate their experience with VR on a 5-point scale (general experience, experience with VR games, experience with VR exergames).

In the next step, we attached the heart rate sensor to the participants' arms and equipped them with a motion tracking suite with 49 reflective markers and the head-mounted device (HMD) for VR. After setting up the participants with the technical equipment, the participants were placed in a virtual room mimicking our real-world laboratory. The virtual laboratory included virtual mirrors to allow participants to familiarize themselves with the current avatar. As soon as they were ready, participants started with one of the two avatars (*perceived as more fit* / *perceived as less fit*) and one of the two latency levels (*system* / *high*) in the reaction wall task for 60 seconds. Next, participants continued with the barbell task. While performing the tasks, we assessed the participants' physical extortion every 20 seconds using the Borg scale. Every 20 seconds, the Borg scale (6-20) was briefly visible in the virtual environment. After receiving the participants' estimation, the Borg scale became invisible again. Following previous work [38], participants answered the BRG, IPQ, and IMI questionnaire directly in VR after completing the tasks. We repeated this procedure for each combination of VISUAL APPEARANCE and LATENCY. After completing all four iterations, participants were debriefed. The study took about one hour to complete and received ethical clearance according to our institute's research policy.

4.5 Apparatus

A designated $4\,m \times 4\,m$ area in the laboratory is tracked by the motion tracking system OptiTrack[6]. Participants wore a special suit with 49 reflective markers to allow tracking of full-body movement. The reflections of the markers are detected and processed by 16 infrared cameras. The cameras, in turn, pass the received signal on to the processing software Motive[7], which interprets the data and forwards it to a dedicated Unity[8] application responsible for translating the raw motion data to a Unity scene rendered to an HMD. We used an HTC Vive[9] to display the virtual environment. For rendering the stream to the HMD, we used a Windows 10 workstation with an Intel i7-8700, 32 GB RAM, and an Nvidia GeForce GTX 1080.

4.6 Participants

We recruited 16 participants (8 male, 8 female) via our institution's mailing list. Participants' age ranged from 18 to 29 years (*M* = 22.38 years, *SD* = 2.87 years). The BMI ranged from 16.24 to 35.01 kg/m^2 (*M* = 22.95 kg/m^2, *SD* = 5.34 kg/m^2). We asked participants to self-rate their fitness level using the SPF. On average they reported 7.00 points (*SD* = 3.23 points) in *Endurance*, 7.81 points (*SD* = 2.59 points) in *Strength*, 7.19 points (*SD* = 2.71 points) in *Flexibility*, 8.06 points (*SD* = 2.51 points) in *Body Composition*, and 7.38 points (*SD* = 3.32 points) in the *Fitness* category. Participants self-rated their experience with VR in general with 1.94 points (*SD* = 0.85 points), with VR games with 1.44 points (*SD* = 0.89 points), and with VR exergames specifically with 1.31 points (*SD* = 0.60 points). All participants were students at our institution and received one credit point for their course of study.

---

[6] https://optitrack.com/

[7] https://optitrack.com/software/motive/

[8] https://unity.com/

[9] https://www.vive.com/us/

5 RESULTS

All gathered data was tested for normality using Shapiro-Wilk tests (normal distribution assumed if $p > .05$). Based on normality, we either used a 2 (Visual Appearance: *perceived as more fit* vs. *perceived as less fit*) x 2 (Latency: *system* vs. *high*) ANOVA (parametric data) or its rank-aligned equivalent ART-ANOVA (non-parametric data) [65]. To increase readability, we only report full results for significant measures in this section for the used questionnaires. However, the complete statistical analysis and descriptive results for all measurements can be found in the Appendix in Tables 1, 2, and 3.

5.1 Perceived Exertion - Borg Scale

ART-ANOVA showed no significant main effect of Visual Appearance or Latency and no interaction effect on the *perceived exertion* for the reaction wall task (all $ps > .083$). Similarly, we did not find a significant main effect of Visual Appearance, Latency nor an interaction effect Visual Appearance × Latency on the *perceived exertion* for the barbell task using ANOVA (all $ps > .149$).

5.2 Body Ownership

ART-ANOVA showed a significant main effect of Visual Appearance on the BRQ scale *vr-body* (F(1,15) = 15.606, $p < .001$, $\eta_p^2 = .257$), but no other main effect or interaction ($ps > .657$). ART-ANOVA also revealed a significant effect of Visual Appearance on *mirror* (F(1,15) = 15.740, $p < .001$, $\eta_p^2 = .259$), but no effect of Latency or Visual Appearance × Latency ($ps > .410$). Again, ART-ANOVA revealed a significant effect of Visual Appearance on *features* (F(1,15) = 11.357, $p = .002$, $\eta_p^2 = .202$), but no effect of Latency or Visual Appearance × Latency ($ps > .682$). Neither Latency nor the interaction with Visual Appearance revealed significant effects on *agency* ($ps > .355$). However, ART-ANOVA showed an significant effect of Visual Appearance on *agency* (F(1,15) = 6.616, $p = .013$, $\eta_p^2 = .128$). Lastly, we found no effect on the *twobodies* subscale of the BRQ ($ps > .303$). In summary, participants had a higher feeling of body ownership and agency when embodying the *perceived as more fit* avatar. Figure 6 depicts all significant differences for each sub-scale of the BRQ.

5.3 Presence and Intrinsic Motivation

ART-ANOVA found a significant effect of Visual Appearance on *experienced realism* (F(1,15) = 15.199, $p = .001$, $\eta_p^2 = .503$), but no effect of Latency and no interaction between Latency and Visual Appearance ($ps > .659$). ANOVA found no effect of Latency, Visual Appearance nor the interaction Latency × Visual Appearance on *general presence* ($ps > .274$). ANOVA found a significant effect of Visual Appearance on *enjoyment* (F(1,15) = 5.209, $p = .037$, $\eta_p^2 = .258$), however, we found no effect of Latency and no interaction ($ps > .289$). ANOVA also showed a significant effect of Visual Appearance on *perceived competence* (F(1,15) = 5.080, $p = .040$, $\eta_p^2 = .253$). However, we found no effect of Latency and no interaction ($ps > .053$). In summary, participants experienced a higher level of realism, enjoyment, and competence when embodying the *perceived as more fit* avatar. Figure 7 depicts the significant differences of *experienced realism*, *enjoyment*, and *perceived competence* within Visual Appearance.

5.4 Performance and Heart Rate

ANOVA showed no significant effect of Visual Appearance or Latency × Visual Appearance on *score* ($ps > .736$). However, we found a significant effect of Latency (F(1,15) = 110.505, $p < .001$, $\eta_p^2 = .880$). ART-ANOVA showed no significant effect of Visual Appearance or Latency × Visual Appearance on *error* ($ps > .386$), but, we found a significant effect of Latency (F(1,15) = 14.845, $p < .002$, $\eta_p^2 = .497$). Neither Latency nor the interaction between Latency and Visual Appearance had a significant effect on the number of *barbell repetitions* ($ps > .390$). Nevertheless, we found an significant effect of Visual Appearance (F(1,15) = 12.23, $p = .034$, $\eta_p^2 = .096$). Participants had a decreased error and obtained a higher score when participating with the *system* latency. Additionally, participants completed more bicep curls when embodying the *perceived as more fit* avatar. We found no effect of either Visual Appearance or Latency nor an interaction between Visual Appearance × Latency on *heart rate* ($ps > .078$). Figure 8 depicts the significant differences of *score* and *error* within Latency. The figure also shows the differences in *barbell repetitions* within Visual Appearance.

6 DISCUSSION

Our analysis revealed that the avatar's visual appearance significantly alters subjective and objective measures in full-body MT VR (RQ_1). We also found that latency reduces the participants' scores and increases their error rate in fast-paced VR tasks. In contrast, we did not find that the avatar's visual appearance and the environment's latency interact (RQ_2). In the following section, we discuss our findings in relation to previous work, highlight our work's limitations, and outline possible avenues for future work.

6.1 Effects of the Visual Appearance of Avatars

Our work replicates and extends prior work investigating the Proteus effect [66, 67], which highlights that the visual appearance of avatars modulates the user's subjective experience and objective performance in VR. According to the Proteus effect, embodying an avatar triggers a top-down process, which alters the user's behavior, attitude, and perception [33, 52]. The same holds in our work. We found that users experienced higher body ownership, realism, enjoyment, and competence when embodying the avatar, which was perceived to be more fit. Moreover, we also found that participants' physical performance was higher when embodying the avatar perceived to be more fit.

The increase in physical performance directly resonates with previous work investigating the Proteus effect. This work demonstrated that embodying avatars that suggest a stereotypical characteristic alters participants' physical capability and behavior, which in turn, engage in stereotype-confirming actions [49]. Kocur et al. [35, 38] and Lin et al. [45], for example, showed that embodying a muscular or athletic avatar leads to altered physical performance in different scenarios, while Reinhard et al. [53] demonstrated that embodying an avatar that looks old results in reduced walking speed. Hence, our finding regarding the increase in barbell repetitions, and thus, the increase in physical performance, can be explained by the Proteus effect.

Our work also revealed that participants experienced higher body ownership when embodying the avatar perceived to be more

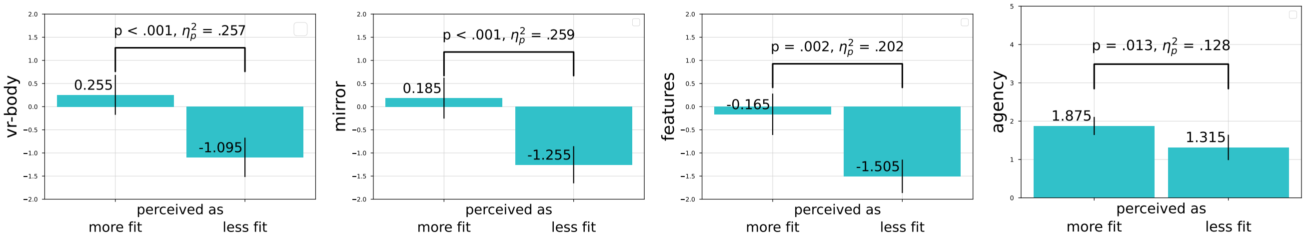

Figure 6: Depicts mean *vr-body* (top left), *mirror* (top right), *features* (bottom left), and *agency* (bottom right) values grouped by VISUAL APPEARANCE. All subfigures provide p-values and effect sizes for the within VISUAL APPEARANCE comparison. Error bars depict the standard error. Participants had a higher feeling of body ownership and agency when embodying the *perceived as more fit* avatar.

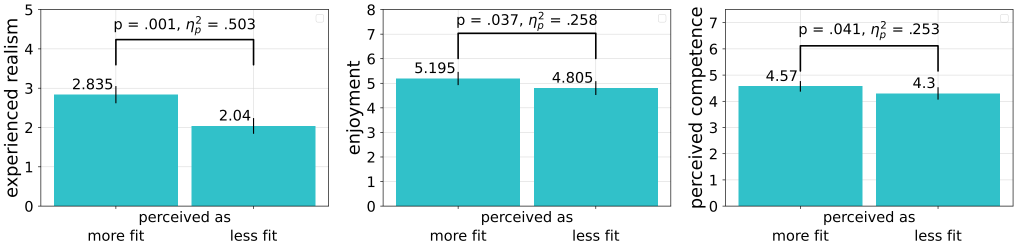

Figure 7: Depicts mean *experienced realism* (left), *enjoyment* (middle), and *perceived competence* (right) values grouped by VISUAL APPEARANCE. All subfigures provide p-values and effect sizes for the within VISUAL APPEARANCE comparison. Error bars depict the standard error. Participants experienced a higher level of realism, enjoyment, and competence when embodying the *perceived as more fit* avatar.

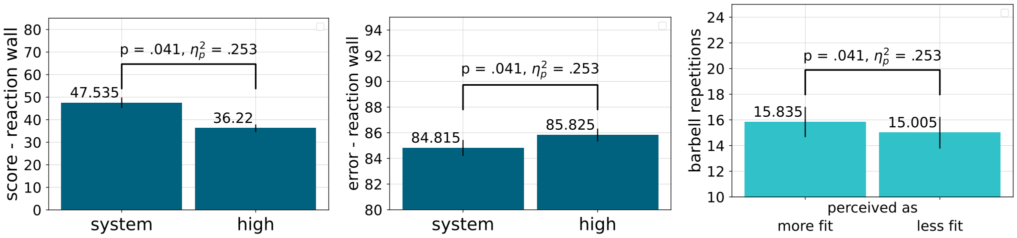

Figure 8: Depicts mean *score - reaction wall* (left) and *error - reaction* (middle) values grouped by LATENCY. Participants scored higher and had a decreased overall error when playing with *system* LATENCY. The right panel shows mean *barbell repetitions* values grouped by VISUAL APPEARANCE. Participants completed more barbell curls when embodying the *perceived as more fit* avatar. All subfigures provide p-values and effect sizes for the respective within-comparison. Error bars depict the standard error.

fit. Body ownership in virtual reality refers to the feeling of owning and controlling a virtual body or avatar as if it were one's own body [29]. Previous work consistently highlighted that the visual appearance of avatars alters the level of body ownership experienced in virtual reality [28, 63]. Jo et al. [28], for example, uncovers that participants generally exhibit a higher sense of body ownership when their avatar visually resembles or mimics their outfit, even if the similarity is relatively low. Waltemate et al. [63] expanded on this work and showed that personalizing avatar appearance to participants leads to an even more significant increase in a feeling of body ownership. The same phenomena led to increased body ownership in our participants when embodying the avatar perceived to be more fit. Although we did not specifically design the avatars' visual appearance in line with our participants, one could argue that the reported self-perceived fitness level and the calculated BMIs of our participants better fit the visual appearance of the avatar perceived to be more fit. Hence, using this avatar resulted in an increase in body ownership and experienced realism.

Furthermore, we found increased enjoyment and perceived competence when embodying the avatar which was perceived to be more fit. We argue that those findings are secondary effects related to a well-researched phenomenon called performance-enjoyment link [32]. The performance-enjoyment link refers to the relationship between performance and enjoyment in different tasks. Previous work showed that participants experience joy and pride when they succeed in difficult challenges. Conversely, performing worse results in an increase of stress and frustration [32]. In our work, participants performed objectively better when embodying the avatar perceived to be more fit, which, in turn, resulted in increased enjoyment and perceived competence.

6.2 Effects of Latency

We found that increasing latency reduces the participants' scores and increases their error rates in the reaction wall task, while the barbell performance was unaffected by latency. Our findings generally are in line with previous work. Caserman et al. [12], for example, demonstrated that user performance in a target selection task conducted in VR decreases starting at 69 ms of latency. Other work, for example, by Schwind et al. [58], also showed that user performance decreases when latency increases in a gamified setting. Despite the dissimilarity between the tasks examined in our study and prior research, they share a common requirement for rapid and precise execution of interactions. Previous research on latency in non-VR video games consistently demonstrates that the degree of latency's impact is highly dependent on a given task's temporal and spatial requirements. Specifically, the faster and more precise the required interaction, the more adverse the effect of latency [14, 16, 17]. Thus, the fast-paced nature of the reaction wall task resulted in decreased participant performance when latency was introduced. Conversely, the barbell task's lack of time pressure and low accuracy requirement rendered it somewhat immune to latency-induced effects.

Contrary to our initial expectations and previous work [31, 47, 58], our findings suggest no significant effects of latency on any of the measured experience factors. Participants reported similar levels of body ownership, presence, immersion, and intrinsic motivation across the different levels of latency induced in our study. These results suggest that the level of latency is not a critical factor affecting the user experience in our study. Our findings indicate that participants in our study may have adapted to the introduced latency and compensated for it subconsciously. Similar latency habituation effects have been observed in non-VR video games [55], where users adjust to a certain level of latency to create a smooth and immersive experience. Therefore, it is possible that a similar adaptation effect influenced the experience results obtained in our study. Furthermore, it is also possible that the tested latency levels were too low. Although previous work demonstrated that user experience could start to decrease at latency levels as low as 40 ms [47], it still is possible that our tasks and the designed study were more robust to latency. Hence, it is possible that the adverse effects of latency were not prominent enough.

6.3 On the Interaction Between Visual Appearance and Latency

Investigating the interaction between the visual appearance of the avatar and the environment's latency revealed no significant effect. Similar to the investigation of main effects induced by latency, it is possible that the tested latency levels were too low to discover an interaction effect with other effectors, such as the visual avatar appearance. Moreover, it is possible that the visual appearance of an avatar and latency in VR do not interact at all. Previous work comparing the effects of latency with and without an avatar came to a similar conclusion [56]. However, in their work, the authors compared the effects of latency when embodying a minimalistic avatar to its effects when participating in VR without any avatar in highly specialized use cases. Although our work and the work by Samaraweera et al. [56] are certainly related, we argue that it is not conclusively clear if and how the avatar's visual appearance alters the effects of latency in VR.

6.4 Limitations and Future Work

While our work replicates and expand on previous findings regarding the Proteus effect and demonstrates the adverse effects of latency on fast-paced full-body MT VR tasks, it still has limitations.

One limitation of our work is that it consisted of two separate studies. The first study was conducted to determine the visual avatar appearances for use in the second study. While conducting two independent studies is less exhausting for participants, it may also introduce variability and inconsistencies between the studies, which can affect the overall reliability of the findings. Therefore, future work should consider conducting the same approach using a single study to increase consistency. By conducting a single study, researchers can ensure that the same group of participants is used to determine and test the avatars with different latency levels. This can minimize the variability and increase the reliability of the findings. Furthermore, conducting a single study can also help reduce the resources required for the research, including time, effort, and cost, which can be important considerations for researchers and organizations.

Another limitation of the study is the lack of body type representation in the chosen avatar's visual appearance. The avatar used in the study may not have represented the diverse range of body types in the real world. This can affect the generalizability of our findings, as the study's results may not apply to individuals with different body types than those represented by the chosen avatar. Additionally, the participant sample used in the study may also limit the generalizability of the findings. The study did not include participants with diverse demographic characteristics, such as age, gender, ethnicity, or cultural background. As a result, the findings may not represent the wider population, and it may not be possible to generalize the study's results to individuals with different demographic characteristics. Therefore, future studies investigating the interaction between latency and visual avatar appearance should consider using avatars that depict diverse visual appearances and include participants with more diverse demographic characteristics. This can help ensure that the findings apply to a broader range of individuals and increase the generalizability of the findings.

On the same note, another limitation of our work is that we used avatars that resemble real humans closely. While human avatars may help represent realistic movements and interactions, they may only be appropriate for some participants. Therefore, future work should consider replicating this study with non-humanoid avatars such as robots. By using non-humanoid avatars, researchers can avoid potential stereotypes and make the avatar appearance more neutral and acceptable to a broader range of participants.

7 CONCLUSION

In this work, we present the results of our investigation into the interaction between an avatar's visual appearance and latency in full-body MT VR. In the first study, 41 participants rated and determined two sets of diametric avatars (each female and male) whose visual appearance is perceived to be more or less fit for two physically demanding tasks. In the second study, 16 participants tested both avatars in two VR tasks while we controlled the latency (system and high) in the virtual environment. Our results show that embodying an avatar perceived as more fit resulted in a higher level of body ownership, experienced realism, enjoyment, and perceived competence (RQ_1). Furthermore, we replicate and expand on previous work on the Proteus effect [33, 66, 67] and show that embodying an avatar that is perceived to be more fit increased the participants' performance (RQ_1). We contextualize those findings and argue that the increase in body ownership stems from participants more closely resembling the avatar, which was perceived to be more fit [63]. Moreover, we discuss that the increase in enjoyment and perceived competence are secondary emotional responses to the objectively increased performance by the Proteus effect [32]. While we found, in line with previous work [14, 16, 22], that latency decreases the participants' performance in the fast-paced task, we did not find an interaction between latency and the avatar's visual appearance (RQ_2).

In summary, although our work suggests that the avatar's visual appearance and latency in virtual environments do not interact, we argue that our work is only a first step into a broader investigation of how the adverse effects of latency can be counteracted by using different avatar appearances. Hence, future studies should further investigate different avatars and avatar accessories, such as clothes or accessories in VR, to learn more about users' perceptual responses to latency.

REFERENCES

[1] Hironori Akiduki, Suetaka Nishiike, Hiroshi Watanabe, Katsunori Matsuoka, Takeshi Kubo, and Noriaki Takeda. 2003. Visual-vestibular conflict induced by virtual reality in humans. *Neuroscience letters* 340, 3 (2003), 197–200.

[2] Rachel Albert, Anjul Patney, David Luebke, and Joohwan Kim. 2017. Latency requirements for foveated rendering in virtual reality. *ACM Transactions on Applied Perception (TAP)* 14, 4 (2017), 1–13.

[3] Christiane Attig, Nadine Rauh, Thomas Franke, and Josef F Krems. 2017. System latency guidelines then and now–is zero latency really considered necessary?. In *International Conference on Engineering Psychology and Cognitive Ergonomics*. Springer, 3–14.

[4] Jeremy Bailenson and Jim Blascovich. 2004. Avatars. In *Encyclopedia of Human-Computer Interaction*. Berkshire Publishing Group, 64–68.

[5] Domna Banakou, Raphaela Groten, and Mel Slater. 2013. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences* 110, 31 (2013), 12846–12851.

[6] Domna Banakou, Parasuram D Hanumanthu, and Mel Slater. 2016. Virtual embodiment of white people in a black virtual body leads to a sustained reduction in their implicit racial bias. *Frontiers in human neuroscience* (2016), 601. https://doi.org/10.3389/fnhum.2016.00601

[7] Domna Banakou, Sameer Kishore, and Mel Slater. 2018. Virtually being Einstein results in an improvement in cognitive task performance and a decrease in age bias. *Frontiers in psychology* (2018), 917. https://doi.org/10.3389/fpsyg.2018.00917

[8] Leilani Battle, R Jordan Crouser, Audace Nakeshimana, Ananda Montoly, Remco Chang, and Michael Stonebraker. 2019. The role of latency and task complexity in predicting visual search behavior. *IEEE transactions on visualization and computer graphics* 26, 1 (2019), 1246–1255.

[9] Daryl J. Bem. 1972. Self-Perception Theory11Development of self-perception theory was supported primarily by a grant from the National Science Foundation (GS 1452) awarded to the author during his tenure at Carnegie-Mellon University. Advances in Experimental Social Psychology, Vol. 6. Academic Press, 1–62. https://doi.org/10.1016/S0065-2601(08)60024-6

[10] Yahn W Bernier. 2001. Latency compensating methods in client/server in-game protocol design and optimization. In *Game Developers Conference*, Vol. 98033.

[11] Gunnar Borg. 1998. *Borg's perceived exertion and pain scales.* Human kinetics.

[12] Polona Caserman, Michelle Martinussen, and Stefan Göbel. 2019. Effects of end-to-end latency on user experience and performance in immersive virtual reality applications. In *Entertainment Computing and Serious Games: First IFIP TC 14 Joint International Conference, ICEC-JCSG 2019, Arequipa, Peru, November 11–15, 2019, Proceedings 1*. Springer, 57–69.

[13] Marie Chancel and H Henrik Ehrsson. 2020. Which hand is mine? Discriminating body ownership perception in a two-alternative forced-choice task. *Attention, Perception, & Psychophysics* 82, 8 (2020), 4058–4083.

[14] Mark Claypool and Kajal Claypool. 2006. Latency and player actions in online games. *Commun. ACM* 49, 11 (2006), 40–45.

[15] Mark Claypool and Kajal Claypool. 2010. Latency Can Kill: Precision and Deadline in Online Games. In *Proceedings of the First Annual ACM SIGMM Conference on Multimedia Systems* (Phoenix, Arizona, USA) *(MMSys '10)*. Association for Computing Machinery, New York, NY, USA, 215–222. https://doi.org/10.1145/1730836.1730863

[16] Mark Claypool and Kajal Claypool. 2010. Latency can kill: precision and deadline in online games. In *Proceedings of the first annual ACM SIGMM conference on Multimedia systems*. 215–222.

[17] Mark Claypool, Andy Cockburn, and Carl Gutwin. 2020. The Impact of Motion and Delay on Selecting Game Targets with a Mouse. *ACM Trans. Multimedia Comput. Commun. Appl.* 16, 2s, Article 73 (jun 2020), 24 pages. https://doi.org/10.1145/3390464

[18] Didier Delignières, A Marcellini, J Brisswalter, and P Legros. 1994. Self-perception of fitness and personality traits. *Perceptual and motor Skills* 78, 3 (1994), 843–851. https://doi.org/10.1177/003151259407800333

[19] Wouter Durnez, Aleksandra Zheleva, Mark Claypool, Klaas Bombeke, Mathias Maes, Jan Van Looy, and Lieven De Marez. 2021. Spaz! The effects of local latency on player actions in an desktop-based exergame. *IEEE Transactions on Games* (2021). https://doi.org/10.1109/TG.2021.3128714

[20] Michael SA Graziano. 1999. Where is my arm? The relative role of vision and proprioception in the neuronal representation of limb position. *Proceedings of the National Academy of Sciences* 96, 18 (1999), 10418–10421. https://doi.org/10.1073/pnas.96.18.10418

[21] Carl Gutwin, Steve Benford, Jeff Dyck, Mike Fraser, Ivan Vaghi, and Chris Greenhalgh. 2004. Revealing delay in collaborative environments. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 503–510.

[22] David Halbhuber, Niels Henze, and Valentin Schwind. 2021. Increasing player performance and game experience in high latency systems. *Proceedings of the ACM on Human-Computer Interaction* 5, CHI PLAY (2021), 1–20.

[23] David Halbhuber, Annika Köhler, Markus Schmidbauer, Jannik Wiese, and Niels Henze. 2022. The Effects of Auditory Latency on Experienced First-Person Shooter Players. In *Proceedings of Mensch und Computer 2022*. 286–296.

[24] David Halbhuber, Maximilian Schlenczek, Johanna Bogon, and Niels Henze. 2022. Better be quiet about it! The Effects of Phantom Latency on Experienced First-Person Shooter Players. In *Proceedings of the 21st International Conference on Mobile and Ubiquitous Multimedia*. 172–181.

[25] David Halbhuber, Valentin Schwind, and Niels Henze. 2022. Don't Break my Flow: Effects of Switching Latency in Shooting Video Games. *Proceedings of the ACM on Human-Computer Interaction* 6, CHI PLAY (2022), 1–20.

[26] David Halbhuber, Maximilian Seewald, Fabian Schiller, Mathias Götz, Jakob Fehle, and Niels Henze. 2022. Using Artificial Neural Networks to Compensate Negative Effects of Latency in Commercial Real-Time Strategy Games. In *Proceedings of Mensch und Computer 2022*. 182–191.

[27] Zenja Ivkovic, Ian Stavness, Carl Gutwin, and Steven Sutcliffe. 2015. Quantifying and Mitigating the Negative Effects of Local Latencies on Aiming in 3D Shooter Games. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 135–144. https://doi.org/10.1145/2702123.2702432

[28] Dongsik Jo, Kangsoo Kim, Gregory F. Welch, Woojin Jeon, Yongwan Kim, Ki-Hong Kim, and Gerard Jounghyun Kim. 2017. The Impact of Avatar-Owner Visual Similarity on Body Ownership in Immersive Virtual Reality. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* (Gothenburg, Sweden) *(VRST '17)*. Association for Computing Machinery, New York, NY, USA, Article 77, 2 pages. https://doi.org/10.1145/3139131.3141214

[29] Sungchul Jung and Charles E. Hughes. 2016. Body Ownership in Virtual Reality. In *2016 International Conference on Collaboration Technologies and Systems (CTS)*. 597–600. https://doi.org/10.1109/CTS.2016.0110

[30] S. W. K. Lee and R. K. C. Chang. 2017. On "shot around a corner" in first-person shooter games. In *2017 15th Annual Workshop on Network and Systems Support for Games (NetGames)*. 1–6. https://doi.org/10.1109/NetGames.2017.7991545

[31] Shunichi Kasahara, Keina Konno, Richi Owaki, Tsubasa Nishi, Akiko Takeshita, Takayuki Ito, Shoko Kasuga, and Junichi Ushiba. 2017. Malleable embodiment: changing sense of embodiment by spatial-temporal deformation of virtual human

body. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 6438–6448. https://doi.org/10.1145/3025453.3025962

[32] Christoph Klimmt, Christopher Blake, Dorothée Hefner, Peter Vorderer, and Christian Roth. 2009. Player performance, satisfaction, and video game enjoyment. In *Entertainment Computing–ICEC 2009: 8th International Conference, Paris, France, September 3-5, 2009. Proceedings 8*. Springer, 1–12.

[33] Martin Kocur. 2022. Utilizing the Proteus Effect to Improve Performance Using Avatars in Virtual Reality. https://epub.uni-regensburg.de/52677/

[34] Martin Kocur, Johanna Bogon, Manuel Mayer, Miriam Witte, Amelie Karber, Niels Henze, and Valentin Schwind. 2022. Sweating Avatars Decrease Perceived Exertion and Increase Perceived Endurance While Cycling in Virtual Reality. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology* (Tsukuba, Japan) *(VRST '22)*. Association for Computing Machinery, New York, NY, USA, Article 29, 12 pages. https://doi.org/10.1145/3562939.3565628

[35] Martin Kocur, Florian Habler, Valentin Schwind, Paweł W. Woźniak, Christian Wolff, and Niels Henze. 2021. Physiological and Perceptual Responses to Athletic Avatars While Cycling in Virtual Reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 519, 18 pages. https://doi.org/10.1145/3411764.3445160

[36] Martin Kocur, Niels Henze, and Valentin Schwind. 2021. The Extent of the Proteus Effect as a Behavioral Measure for Assessing User Experience in Virtual Reality. In *CHI 2021 - Workshop on Evaluating User Experiences in Mixed Reality*. 1–3. https://epub.uni-regensburg.de/45543/

[37] Martin Kocur, Lukas Jackermeier, Valentin Schwind, and Niels Henze. 2023. The Effects of Avatar and Environment on Thermal Perception and Skin Temperature in Virtual Reality. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. https://doi.org/10.1145/3544548.3580668

[38] Martin Kocur, Melanie Kloss, Valentin Schwind, Christian Wolff, and Niels Henze. 2020. Flexing muscles in virtual reality: effects of avatars' muscular appearance on physical performance. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*. 193–205.

[39] Martin Kocur, Philipp Schauhuber, Valentin Schwind, Christian Wolff, and Niels Henze. 2020. The Effects of Self- and External Perception of Avatars on Cognitive Task Performance in Virtual Reality. In *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology* (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 27, 11 pages. https://doi.org/10.1145/3385956.3418969

[40] Elena Kokkinara and Mel Slater. 2014. Measuring the Effects through Time of the Influence of Visuomotor and Visuotactile Synchronous Stimulation on a Virtual Body Ownership Illusion. *Perception* 43 (2014), 43–58. Issue 1. https://doi.org/10.1068/p7545

[41] Jordan Koulouris, Zoe Jeffery, James Best, Eamonn O'Neill, and Christof Lutteroth. 2020. Me vs. Super(Wo)Man: Effects of Customization and Identification in a VR Exergame. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (2020), 1–17. https://doi.org/10.1145/3313831.3376661

[42] Injung Lee, Sunjun Kim, and Byungjoo Lee. 2019. Geometrically compensating effect of end-to-end latency in moving-target selection games. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12. https://doi.org/10.1145/3290605.3300790

[43] Jih-Hsuan Tammy Lin and Dai-Yun Wu. 2021. Exercising With Embodied Young Avatars: How Young vs. Older Avatars in Virtual Reality Affect Perceived Exertion and Physical Activity Among Male and Female Elderly Individuals. *Frontiers in psychology* 12 (2021). https://doi.org/10.3389/fpsyg.2021.693545

[44] Jih-Hsuan Tammy Lin, Dai-Yun Wu, and Ji-Wei Yang. 2021. Exercising With a Six Pack in Virtual Reality: Examining the Proteus Effect of Avatar Body Shape and Sex on Self-Efficacy for Core-Muscle Exercise, Self-Concept of Body Shape, and Actual Physical Activity. *Frontiers in psychology* 12 (2021). https://doi.org/10.3389/fpsyg.2021.693543

[45] Jih-Hsuan Tammy Lin, Dai-Yun Wu, and Ji-Wei Yang. 2021. Exercising with a six pack in virtual reality: Examining the proteus effect of avatar body shape and sex on self-efficacy for core-muscle exercise, self-concept of body shape, and actual physical activity. *Frontiers in psychology* (2021), 4580.

[46] Shengmei Liu, Xiaokun Xu, and Mark Claypool. 2022. A survey and taxonomy of latency compensation techniques for network computer games. *ACM Computing Surveys (CSUR)* 54, 11s (2022), 1–34.

[47] Michael Meehan, Sharif Razzaque, Mary C Whitton, and Frederick P Brooks. 2003. Effect of latency on presence in stressful virtual environments. In *IEEE Virtual Reality, 2003. Proceedings.* IEEE, 141–148. https://doi.org/10.1109/VR.2003.1191132

[48] Robert B. Miller. 1968. Response Time in Man-Computer Conversational Transactions. In *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I* (San Francisco, California) *(AFIPS '68 (Fall, part I))*. Association for Computing Machinery, New York, NY, USA, 267–277. https://doi.org/10.1145/1476589.1476628

[49] Akimi Oyanagi, Takuji Narumi, Jean-Luc Lugrin, Kazuma Aoyama, Kenichiro Ito, Tomohiro Amemiya, and Michitaka Hirose. 2022. The Possibility of Inducing the Proteus Effect for Social VR Users. In *HCI International 2022–Late Breaking Papers: Interacting with eXtended Reality and Artificial Intelligence: 24th International Conference on Human-Computer Interaction, HCII 2022, Virtual Event, June 26–July 1, 2022, Proceedings*. Springer, 143–158.

[50] Jorge Peña, Subuhi Khan, and Cassandra Alexopoulos. 2016. I Am What I See: How Avatar and Opponent Agent Body Size Affects Physical Activity Among Men Playing Exergames. *Journal of Computer-Mediated Communication* 21 (2016), 195–209. Issue 3. https://doi.org/10.1111/jcc4.12151

[51] Jorge Peña and Eunice Kim. 2014. Increasing Exergame Physical Activity through Self and Opponent Avatar Appearance. *Computers in Human Behavior* 41 (2014), 262–267. Issue C. https://doi.org/10.1016/j.chb.2014.09.038

[52] Rabindra Ratan, David Beyea, Benjamin J. Li, and Luis Graciano. 2019. Avatar characteristics induce users' behavioral conformity with small-to-medium effect sizes: a meta-analysis of the proteus effect. *Media Psychology* 3269 (2019). https://doi.org/10.1080/15213269.2019.1623698

[53] René Reinhard, Khyati Girish Shah, Corinna A. Faust-Christmann, and Thomas Lachmann. 2020. Acting your avatar's age: effects of virtual reality avatar embodiment on real life walking speed. *Media Psychology* 23, 2 (2020), 293–315. https://doi.org/10.1080/15213269.2019.1598435

[54] Richard M Ryan. 1982. Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of personality and social psychology* 43, 3 (1982), 450.

[55] Saeed Shafiee Sabet, Steven Schmidt, Carsten Griwodz, and Sebastian Möller. 2019. Towards the impact of Gamers' adaptation to delay variation on gaming quality of experience. In *2019 Eleventh international conference on quality of multimedia experience (QoMEX)*. IEEE, 1–6.

[56] Gayani Samaraweera, Rongkai Guo, and John Quarles. 2013. Latency and avatars in virtual environments and the effects on gait for persons with mobility impairments. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 23–30.

[57] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments* 10, 3 (2001), 266–281.

[58] Valentin Schwind, David Halbhuber, Jakob Fehle, Jonathan Sasse, Andreas Pfaffelhuber, Christoph Tögel, Julian Dietz, and Niels Henze. 2020. The Effects of Full-Body Avatar Movement Predictions in Virtual Reality Using Neural Networks. In *26th ACM Symposium on Virtual Reality Software and Technology* (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 28, 11 pages. https://doi.org/10.1145/3385956.3418941

[59] Valentin Schwind, Pascal Knierim, Cagri Tasci, Patrick Franczak, Nico Haas, and Niels Henze. 2017. "These Are Not My Hands!": Effect of Gender on the Perception of Avatar Hands in Virtual Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1577–1582. https://doi.org/10.1145/3025453.3025602

[60] Valentin Schwind, Lorraine Lin, Massimiliano Di Luca, Sophie Jörg, and James Hillis. 2018. Touch with Foreign Hands: The Effect of Virtual Hand Appearance on Visual-Haptic Integration. In *Proceedings of the ACM Symposium on Applied Perception (SAP '18)* (2018-08-03). ACM, New York, NY. https://doi.org/10.1145/3225153.3225158

[61] Sofia Seinfeld, Tiare Feuchtner, Antonella Maselli, and Jörg Müller. 2021. User Representations in Human-Computer Interaction. *Human–Computer Interaction* 36 (2021), 400–438. Issue 5-6. https://doi.org/10.1080/07370024.2020.1724790

[62] Jan-Philipp Stauffert, Florian Niebling, and Marc Erich Latoschik. 2018. Effects of latency jitter on simulator sickness in a search task. In *2018 IEEE conference on virtual reality and 3D user interfaces (VR)*. IEEE, 121–127.

[63] Thomas Waltemate, Dominik Gall, Daniel Roth, Mario Botsch, and Marc Erich Latoschik. 2018. The impact of avatar personalization and immersion on virtual body ownership, presence, and emotional response. *IEEE transactions on visualization and computer graphics* 24, 4 (2018), 1643–1652.

[64] Raphael Wimmer, Andreas Schmid, and Florian Bockes. 2019. On the Latency of USB-Connected Input Devices. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.

[65] Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 143–146.

[66] Nick Yee and Jeremy Bailenson. 2007. The Proteus effect: The effect of transformed self-representation on behavior. *Human communication research* 33, 3 (2007), 271–290. https://doi.org/10.1111/j.1468-2958.2007.00299.x

[67] Nick Yee, Jeremy N Bailenson, and Nicolas Ducheneaut. 2009. The Proteus effect: Implications of transformed digital self-representation on online and offline behavior. *Communication Research* 36, 2 (2009), 285–312. https://doi.org/doi.org/10.1177/009365020833025

APPENDIX

Descriptive Results of all Measures								
	Avatar A / System		**Avatar A / High**		**Avatar B / System**		**Avatar B/ High**	
Measure	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Perceived Exertion Task 1	8.19	1.56	9.27	2.61	9.54	2.21	9.94	3.75
Perceived Exertion Task 2	10.03	2.01	10.91	2.93	10.69	2.44	10.53	2.52
Vr-body (BRQ)	0.13	1.63	-1.13	1.71	0.38	1.82	-1.06	1.69
Mirror (BRQ)	0.31	1.66	-1.13	1.54	0.06	1.88	-1.38	1.67
Feature (BRQ)	-0.13	1.78	-1.38	1.50	-0.19	1.80	-1.63	1.26
Agency (BRQ)	2.00	0.89	1.38	1.36	1.75	1.00	1.25	1.29
Twobodies (BRQ)	-0.81	1.76	-0.63	1.36	-0.69	1.20	-0.38	1.96
General presences (IPQ)	4.25	0.58	3.81	1.42	4.00	1.03	3.56	1.15
Experienced realism (IPQ)	2.78	0.89	2.03	0.76	2.89	0.86	2.05	0.84
Enjoyment (IMI)	5.36	1.09	4.84	1.17	5.03	1.07	4.77	1.09
Perceived Competence	4.79	0.64	4.51	0.84	4.35	0.98	4.09	1.05
Score (reaction wall)	47.44	9.67	47.63	8.97	36.69	7.10	35.75	6.33
Error rate (reaction wall)	84.82	2.21	84.81	3.18	86.08	1.86	85.57	2.21
Repetitions (barbell)	16.44	5.20	15.38	5.23	15.63	4.23	14.63	4.65
Heart rate (reaction wall)	102.28	12.55	103.47	13.05	103.99	16.97	103.26	14.75
Heart rate (barbell)	100.57	15.00	99.33	15.30	101.56	15.89	102.04	14.80

Table 1: Depicts the descriptive results of all measures of the second study for all combinations of VISUAL APPEARANCE/LATENCY. Because of character limitations, we replaced the original identifier of the levels of VISUAL APPEARANCE with shorter placeholders. Avatar A refers to the *perceived as more fit* avatar, while Avatar B refers to the *perceived as less fit* Avatar.

(ART)-ANOVAs of Performance Measures and Heart Rate					
Measure	**Effector**	**DF, Residual**	**F-Value**	**p-Value**	**eta2p**
Score (reation wall)*	Visual Appearance	1, 15	.118	.738	.008
	Latency	**1, 15**	**110.505**	**<.001**	**.880**
	Visual Appearance x Latency	1, 15	.110	.747	.007
Error rate (reation wall)*	Visual Appearance	1, 15	2.118	.151	.124
	Latency	**1, 15**	**14.845**	**.002**	**.497**
	Visual Appearance x Latency	1, 15	.437	.519	.028
Repetitions (barbell)	**Visual Appearance**	**1, 15**	**12.23**	**.034**	**.096**
	Latency	1, 15	.755	.390	.016
	Visual Appearance x Latency	1, 15	.330	.569	.007
Heart rate (reation wall)*	**Visual Appearance**	1, 15	.348	.564	.023
	Latency	1, 15	454	.511	.023
	Visual Appearance x Latency	1, 15	.348	.564	.029
Heart rate (barbell)*	Visual Appearance	1, 15	.197	.663	.013
	Latency	1, 15	3.580	.078	.193
	Visual Appearance x Latency	1, 15	.546	.471	.035

Table 2: Depicts the full statistical results of the second study for the performance measures and heart rate. Significant results are bold. An asterisks at the measure denotes if an ANOVA(*) or an ART-ANOVA was used to analyse this measure.

(ART)-ANOVAs of Perceived Exertion and Body Representation Questionnaire

Measure	**Effector**	**DF, Residual**	**F-Value**	**p-Value**	**eta2p**
Perceived Exertion Task 1	Visual Appearance	1, 15	.400	.530	.009
	Latency	1, 15	3.136	.083	.065
	Visual Appearancex Latency	1, 15	1.413	.241	.030
Perceived Exertion Task 2 (*)	Visual Appearance	1, 15	2.318	.149	.134
	Latency	1, 15	.258	.619	.017
	Visual Appearance x Latency	1, 15	1.183	.294	.073
Vr-body (BRQ)	**Visual Appearance**	**1, 15**	**15.606**	**.001**	**.257**
	Latency	1, 15	.200	.657	.004
	Visual Appearance x Latency	1, 15	.061	.806	.001
Mirror (BRQ)	**Visual Appearance**	**1, 15**	**15.740**	**<.001**	**.259**
	Latency	1, 15	.692	.410	.015
	Visual Appearance x Latency	1, 15	.002	.965	<.001
Feature (BRQ)	**Visual Appearance**	**1, 15**	**11.357**	**.002**	**.202**
	Latency	1, 15	.170	.682	.004
	Visual Appearance x Latency	1, 15	.026	.873	.001
Agency (BRQ)	**Visual Appearance**	**1, 15**	**6.616**	**.013**	**.128**
	Latency	1, 15	.874	.355	.019
	Visual Appearance x Latency	1, 15	.058	.811	.001
Twobodies (BRQ)	Visual Appearance	1, 15	1.085	.303	.024
	Latency	1, 15	.569	.455	.012
	Visual Appearancex Latency	1, 15	<.001	.999	<.001
General presence (IPQ)*	Visual Appearance	1, 15	1.064	.308	.023
	Latency	1, 15	1.226	.274	.027
	Visual Appearance x Latency	1, 15	.096	.758	.002
Experienced realism (IPQ)	**Visual Appearance**	**1, 15**	**15.199**	**.001**	**.503**
	Latency	1, 15	.203	.659	.013
	Visual Appearance x Latency	1, 15	.102	.753	.007
Enjoyment (IMI)*	**Visual Appearance**	**1, 15**	**5.210**	**.037**	**.258**
	Latency	1, 15	1.210	.289	.075
	Visual Appearance x Latency	1, 15	.718	.410	.046
Perceived competence (IMI)*	**Visual Appearance**	**1, 15**	**5.080**	**.040**	**.253**
	Latency	1, 15	4.403	.053	.227
	Visual Appearance x Latency	1, 15	.006	.983	<.0001
Score (reaction wall)*	Visual Appearance	1, 15	.118	.738	.008
	Latency	**1, 15**	**110.505**	**<.001**	**.880**
	Visual Appearance x Latency	1, 15	.110	.745	.007
Error rate (reaction wall)*	Visual Appearance	1, 15	.799	.386	.051
	Latency	**1, 15**	**14.845**	**.002**	**.497**
	Visual Appearance x Latency	1, 15	.437	.519	.028
Repetitions (barbell)	**Visual Appearance**	**1, 15**	**12.23**	**.034**	**.096**
	Latency	1, 15	.755	.390	.016
	Visual Appearance x Latency	1, 15	.330	.569	.007
Heart rate (reaction wall)*	Visual Appearance	1, 15	.074	.789	.005
	Latency	1, 15	.348	.564	.023
	Visual Appearance x Latency	1, 15	.454	.511	.029
Heart rate (barbell)*	Visual Appearance	1, 15	.197	.663	.013
	Latency	1, 15	3.580	.078	.193
	Visual Appearance x Latency	1, 15	.546	.471	.035

Table 3: Depicts the full statistical results of the second study for the Perceived Exertion, Body Representation Questionnaire (BRQ), Igroup Presence Questionnaire (IPQ), and the Intrinsic Motivation Inventory (IMI). Significant results are bold. An asterisks at the measure denotes if an ANOVA(*) or an ART-ANOVA was used to analyse this measure.