Universität Regensburg

Utilizing the Proteus Effect to Improve Performance Using Avatars in Virtual Reality

Inaugural-Dissertation zur Erlangung der Doktorwürde der Fakultät für Sprach-, Literatur- und Kulturwissenschaften der Universität Regensburg

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aus Oberviechtach

2022

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Zusammenfassung

In der virtuellen Realität können Benutzer:innen einen virtuellen Körper besitzen—ein Phänomen, das allgemein als Körperbesitz-Illusion bekannt ist. Forscher und Designer zielen darauf ab, die Körperbesitz-Illusion mit Hilfe von Avataren—virtuellen Figuren, die Benutzer:innen in der digitalen Welt repräsentieren—zu induzieren, um verkörperte Erlebnisse in der virtuellen Realität zu ermöglichen. Im Einklang mit der realen Welt, in der der Mensch einen Körper besitzt und über den Körper mit der Umwelt interagiert, ermöglichen Avatare den Benutzer:innen, auf natürliche und intuitive Weise mit virtuellen Welten zu interagieren. Interessanterweise zeigten frühere Arbeiten, dass das Aussehen eines Avatars das Verhalten, die Einstellung und die Wahrnehmung der Benutzer:innen verändern kann. So wurde beispielsweise festgestellt, dass Benutzer:innen, die attraktive oder große Avatare verkörperten, sich in einer virtuellen Umgebung selbstbewusster verhielten als jene, die weniger attraktive oder kleinere Avatare verkörperten. In Anspielung auf die Vielseitigkeit des griechischen Gottes Proteus, der Erzählungen zufolge seine Gestalt nach Belieben verändern konnte, wurde dieses Phänomen Proteus-Effekt genannt. Für Designer und Forscher von Anwendungen in der virtuellen Realität ist der Proteus-Effekt daher ein interessantes und vielversprechendes Phänomen, um die Benutzer:innen bei der Interaktion in virtuellen Umgebungen positiv zu beeinflussen. Der grenzenlose Gestaltungsspielraum, den die virtuelle Realität bietet, kann genutzt und Avatare mit bestimmten Merkmalen geschaffen werden, die die Interaktion und Leistung der Benutzer:innen in virtuellen Umgebungen verbessern. Um von diesem Phänomen zu profitieren, ist es wichtig zu verstehen, wie solche Avatare und deren Eigenschaften gestaltet werden sollen, um effektivere Anwendungen in der virtuellen Realität zu entwickeln und verbesserte Benutzungserlebnisse zu generieren. Daher werden in dieser Arbeit

der Proteus-Effekt und die zugrundeliegenden Mechanismen mit dem Ziel untersucht, mehr über die Verkörperung von Avataren und die Gestaltung effektiver Avatare zu lernen.

In dieser Dissertation werden die Ergebnisse von fünf Nutzer:innenstudien vorgestellt, die sich mit der Verkörperung von Avataren befassen und damit, wie bestimmte Eigenschaften genutzt werden, damit Benutzer:innen in virtuellen Umgebungen mehr leisten können als sie es in anderen Avataren tun würden. Es werden Methoden erforscht, um ein Gefühl der Verkörperung von Avataren zu induzieren, und die daraus resultierenden wahrnehmungsbezogenen und physiologischen Konsequenzen für den echten Körper kennenzulernen. Außerdem wird untersucht, ob und wie der Realismus eines Avatars und veränderte Körperstrukturen das Erlebnis beeinflussen. Dieses Wissen wird dann genutzt, um eine Verkörperung von Avataren mit Merkmalen zu induzieren, die mit einer hohen Leistungsfähigkeit bei physischen und kognitiven Aufgaben assoziiert werden. Dadurch soll die Leistungsfähigkeit von Benutzer:innen in physisch und kognitiv anspruchsvollen Aufgaben in der virtuellen Realität verbessert werden. In dieser Arbeit wurde festgestellt, dass muskulöse und athletische Avatare die körperliche Leistung bei Anstrengung in der virtuellen Realität steigern können. Des Weiteren wurde herausgefunden, dass ein Einstein-Avatar die Leistung eines anderen sich im virtuellen Raum befindenden Nutzers bei kognitiv anspruchsvollen Aufgaben steigern kann. Diese Arbeit endet mit Gestaltungsrichtlinien und Implikationen für die Nutzung des Proteus-Effekts im Kontext der Mensch-Computer-Interaktion und virtuellen Realität.

Abstract

Virtual reality allows users to experience a sense of ownership of a virtual body—a phenomenon commonly known as the body ownership illusion. Researchers and designers aim at inducing a body ownership illusion and creating embodied experiences using avatars—virtual characters that represent the user in the digital world. In accordance with the real world where humans own a body and interact via the body with the environment, avatars thereby enable users to interact with virtual worlds in a natural and intuitive fashion. Interestingly, previous work revealed that the appearance of an avatar can change the behavior, attitude, and perception of the embodying user. For example, research found that users who embodied attractive or tall avatars behaved more confidently in a virtual environment than those who embodied less attractive or smaller avatars. Alluding to the versatility of the Greek God Proteus who was said to be able to change his shape at will, this phenomenon was termed the Proteus effect. For designers and researchers of virtual reality applications, the Proteus effect is therefore an interesting and promising phenomenon to positively affect users during interaction in virtual environments. They can benefit from the limitless design space provided by virtual reality and create avatars with certain features that improve the users' interaction and performance in virtual environments. To utilize this phenomenon, it is crucial to understand how to design such avatars and their characteristics to create more effective virtual reality applications and enhanced experiences. Hence, this work explores the Proteus effect and the underlying mechanisms with the aim to learn about avatar embodiment and the design of effective avatars.

This dissertation presents the results of five user studies focusing on the body ownership of avatars, and how certain characteristics can be harnessed to make users perform

better in virtual environments than they would in casual embodiments. Hence, we explore methods for inducing a sensation of body ownership of avatars and learn about perceptual and physiological consequences for the real body. Furthermore, we investigate whether and how an avatar's realism and altered body structures affect the experience. This knowledge is then used to induce body ownership of avatars with features connected with high performance in physical and cognitive tasks. Hence, we aim at enhancing the users' performance in physically and cognitively demanding tasks in virtual reality. We found that muscular and athletic avatars can increase physical performance during exertion in virtual reality. We also found that an Einstein avatar can increase the cognitive performance of another user sharing the same virtual environment. This thesis concludes with design guidelines and implications for the utilization of the Proteus effect in the context of human-computer interaction and virtual reality.

Acknowledgments

As I started the journey to become an academic, I thought it would be impossible for me to write and finish a doctoral thesis. Now, I know that I was right: this work would have never been possible without the tremendous support of a number of amazing and inspiring people. I want to take the time to acknowledge their contribution and thank them from the bottom of my heart. I sincerely apologize to everybody I forgot to mention.

First, I want to thank Niels Henze and Valentin Schwind. You showed me the world of scientific research and academia and created such an exciting, pleasant, and prospering work environment. Even in busy times, you were so patient and supportive, and your door was always open to having a chat about research and beyond. You mastered taking away my fear and uncertainty and gave me invaluable advice on how to successfully finish a Ph.D. I am deeply grateful that I met you both. This work would have never been possible without you.

I thank my doctoral supervisor, Prof. Christian Wolff, for his trust, support, and freedom in my research and teaching activities. I am so thankful that you gave me the chance to start this journey, and I have always felt honored to work for your lab. The time will take a special place in my heart.

I thank Michael Lankes for being my second examiner. You showed me the world of game design and always helped me with your input and feedback. Your lectures inspired me a lot. Thank you.

Of course, I thank my colleagues that integrated me into the team, supported me, and gave me a lot of advice: Martin Brockelmann (thank you for showing and teaching me the amazing world of 3D modeling), Alexander Bazo (thank you for sharing your office with me and being so incredibly supportive), Thomas Schmidt (I loved talking about basketball and the Clippers), Alexander Kalus (thank you for your amazing work and effort that you put into your great Master thesis), Andreas Schmid (sorry for painting your great prototype), Johanna Bogon (thank you for sharing your amazing methodological and statistical skills), Daniel Isemann and Patricia Böhm (thank you for your inspiring research seminar where I realized that doing research is great), Martin Dechant (thanks for your support and teaching me how to create games), David Halbhuber (thanks for sharing your technical skills), and Susanne Klinger (thank you for supporting me in all the complex organizational concerns and beyond). I also thank Florian Bockes, Rufat Rzayev, Florin Schwappach, Valentin Lohmüller, Jakob Fehle, Jürgen Hahn, Raphael Wimmer, Victoria Böhm, Michael Achmann, Vitus Maierhöfer, Rebecca Reutter, Thomas Wilhelm, Preetha Morthy, Ingrid Stitz, and Sarah Thanner for being great colleagues.

I am lucky to work with a number of great students that significantly contributed to this thesis: Florian Habler, Philipp Schauhuber, Melanie Kloss, and Sarah Graf. You did a great job and supported me so much. I also thank all my co-authors for their great input, advice, and help. I learned a lot from all of you.

I would also like to thank my friends who supported me throughout different stages of my life, during good as well as tough times: Jonas Joachimsmeyer, Murat Firat, Bryan Boglin, Eduard Sabeko, Patrick Klöbzig, Peter Zuravlev, Michael Lösch, Waldemar Brilz, and the entire basketball crew. Further thanks go to the two cutest dogs in the world, Kairo and Emma, who can always put a smile on my face. I also want to thank my girlfriend's mother Edeltraud Schwarzinger, and her partner Martin Karl for a great trip to Thailand and for having funny evenings while playing cards. I thank Konstantin Schmidt and Katrin Schwarzinger for supporting me in all repairs and installations at home. I also thank Silas and Vito for visiting us at home and having a good time together. I want to thank the rest of the Schwarzinger family for welcoming me so warmly.

I would like to especially thank my mom and dad, Christine and Andreas, who raised the man that I am today and taught me everything I need to know to be a good person. Whenever I am scared and worried, you can lift my spirit and power me up like no one else in the world. Thank you for being who you are and always supporting me unconditionally. I also thank my older brother Simon for sharing all his knowledge and showing me the world since I have been a little kid. You have always been a great big brother, and I have learned a lot from you. I also thank my sister Katharina for her support and advice. You bought my first notebook to support me as an undergraduate student. Thank you so much for your help.

My deepest gratitude is owed to my beautiful and incredibly loving partner Stefanie Schwarzinger. You have unconditionally supported me since day one. Thank you for your love, advice, help, and patience. Day after day, you inspire me with your warmth, wisdom, knowledge, and untiring diligence. You were always supportive, sympathetic, and considerate when work was intense and put everything else aside. You cannot imagine how thankful I am for having you by my side. Thank you from the bottom of my heart.

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Introduction

The field of human-computer interaction (HCI) aims at creating computer systems that enable humans to interact with them in an effective, efficient, and satisfying way (Hewett et al., 1992; Nielsen, 1994). Hence, the interface between humans and computing systems is essential to ensure an appealing and successful interaction. Interactive interfaces either require the user to be represented in the digital world to allow them to execute actions within it (e.g., by a mouse cursor) or enable them to directly interact with the digital content (e.g., via touchscreens; Seinfeld et al., 2021). In these today's typical ways of interacting with computer systems, the digital world is separated from the physical world so that the devices act as a window to the digital world while the interface provides access to its content (Gobbetti & Scateni, 1998; Sutherland, 1965). In recent years, however, *virtual reality* (VR) technologies have evolved and merged these two worlds by completely surrounding the users and creating the sensation of being present and physically existing in the digital world (Rekimoto & Nagao, 1995). Hence, immersive *virtual environments* (VEs) require different approaches of representing the user and providing tools to perform actions within the digital realm.

Designers and researchers of VR applications commonly use *avatars*—the digital self-representation of the user—to provide users with a virtual body in VR and create embodied experiences. Similar to the real world, where the own body is a fundamental part of the self and is a vehicle for interacting with the environment, avatars, therefore, allow a natural and familiar interaction with immersive virtual worlds. In VR, the users' physical body can be spatially replaced by the virtual body when they see the avatar from a first-person perspective through a head-mounted display (HMD). When users look down at their own physical body, they see the avatar's body instead. Today's tracking technologies even allow registering the movements of the entire body so that the motion can be transferred onto the virtual skeleton of the avatar. Consequently, the users' body parts can be rendered in VR according to their real position. Hence, the avatar "mimics" the motion in real time so that users can experience the virtual body as their own one and therefore accept the avatar as the virtual alter ego (Roth & Latoschik, 2020). This phenomenon is commonly known as the *body ownership illusion* (BOI; Kilteni et al., 2015; Maselli & Slater, 2013; Roth & Latoschik, 2020). As VR can render the avatar in any desired style, users can thereby embody any possible appearance while interacting within VEs.

Previous work found that BOIs not only contribute to an enhanced and more natural VR experience (Steed et al., 2016b), they have also the potential to change users' attitudes, perception, and behavior depending on the appearance and properties of the virtual avatar. Such changes are attributed to the *Proteus effect* (Yee & Bailenson, 2007). Yee and Bailenson (2007) revealed that being in a more attractive avatar increases self-confidence indicated by interpersonal distances and self-disclosure in a dialogue in VR. They showed similar results in a second experiment where they manipulated the height of avatars as height is associated with self-esteem and competence. In a VR bargaining task, participants embodied in taller avatars behaved more confidently and performed better in negotiation than when embodied in smaller avatars (Yee & Bailenson, 2007). It has been shown that behavioral and attitudinal changes even retained after the VR experience. Banakou et al. (2018) found that embodying Albert Einstein as a stereotype for superior intelligence could increase cognitive task performance after the VR experience. Such findings demonstrate the potential of experiencing body ownership of certain avatars to improve the users' performance and positively affect them during and after the VR experience. As the avatar acts as an interface between the digital and the real world, the Proteus effect, therefore, seems to be a promising method to create more effective, efficient, and satisfying VR experiences.

Due to the endless number of design choices, however, it is difficult to know how to create avatars with certain characteristics to systematically affect users in a targeted way and improve their performance. Without the knowledge about the psychological mechanisms underlying the correlates of the virtual embodiment, designers and researchers can hardly take advantage of an avatar's attributes to positively affect the user while interacting in VR. Besides, VR experiences including avatar embodiment could also cause adverse effects on the user in case of inappropriate usage. Peña et al. (2016) found that players of a competitive virtual tennis game were physically less active when playing with an avatar the authors dubbed "obese" compared to a normal avatar. While previous studies mainly focused on the proof of concept of avatars as a tool to induce behavioral changes in different scenarios and contexts (Ratan et al., 2019), the systematic investigation of an avatar's visual characteristics that are mainly responsible for changes in perception and behavior has been neglected. From an HCI perspective, it is, therefore, crucial to gain a deeper understanding of the Proteus effect to learn how to utilize it on the one hand, and how to avoid negative consequences on the other.

As the users' performance during tasks is one of the key quality metrics of interactive applications (Nielsen & Levy, 1994), the work presented in this thesis aims to improve performance in VR by focusing on the design of avatars. Specifically, we investigate in this dissertation how we can improve performance in VR using the Proteus effect induced by the mere visual appearance of avatars. We hypothesize that the visual characteristics of an avatar in VR can be manipulated in a way that users will perform tasks better than they would perform them using a casual embodiment. To improve physical performance, we use muscular and athletic avatars to prime concepts that are connected with high physical abilities. We also use an Einstein avatar to improve cognitive performance as Albert Einstein serves as a stereotype for superior intelligence. We, therefore, aim at understanding the cognitive processes underlying body ownership and changes in self-perception and apply this knowledge to design more effective avatars for VR. Hence, the goal of this dissertation is to derive guidelines referring to the visual appearance of avatars, and support researchers and designers in the avatar creation process for improving user performance in VR.

This chapter first clarifies the terminology used throughout the thesis to reach a common understanding of the important terms. Afterward, the Proteus effect is introduced by providing an overview of this phenomenon and discussing the background and etymology. Furthermore, the research questions, the methodological approach, and the contributions of this thesis are presented. The publications are listed and the personal contribution is declared. Finally, an outline of this dissertation is provided by listing the chapters and briefly summarizing their content.

The introduction refers to the following publication that introduces the ideas of this thesis:

Kocur, M., Schwind, V., & Henze, N. (2019). "Utilizing the Proteus Effect to Improve Interactions using Full-Body Avatars in Virtual Reality." In: *Mensch und Computer 2019 - Workshopband*. Bonn: Gesellschaft für Informatik e.V.. DOI: 10.18420/muc2019-ws-584.

1.1 Avatars

First, we clarify the term avatar and distinguish it from other virtual entities in VEs to create a shared understanding of the crucial concepts in this thesis. The term avatar is derived from the Hindu "avatara" which can be translated as "descent" meaning "to come down" or "to go down" (Parrinder, 1997). Even if the term was also translated as "birth", "appearance", or "creation" (Miranda, 1990), the basic meaning is "incarnation" describing the descent of a god on earth in terrestrial shapes (Sukdaven, 2012). In a systematic literature review about the evolution of Hindu deities, Sukdaven (2012) concluded that an "avatara" is a manifestation of a god in the form of a living entity such as a human being or animal. Banks (2018) transferred this idea to avatars in videogames by stating that whereas "Hindu deities descend by taking physical forms, players descend into a gameworld by taking on digital bodies". Hence, in digital worlds, an avatar is a computer-generated entity serving as the user's self-representation. As such, there is a variety of different types of avatars that represent the user in VEs. Schiano and White (1998) analyzed multi-user dungeons—multiplayer text-based adventure games—where users are textually represented without using any graphical representation. Avatars are not only limited to be visual depictions, they can be any kind of mediated user representation such as an auditory entity like a voice (Bailenson et al., 2006; Nowak & Fox, 2018). According to Yee (2007), who created a framework to depict different types of human representations (see Figure 1.1), avatars can range from textual self-representations to social network profiles to realistic and anthropomorphic 3D characters found in today's video games and VR applications (Nowak & Fox, 2018). Based on their framework considering any kind of representation of a human being as an avatar (e.g., physical avatars such as puppets, robots, or even automobiles; Ratan, 2019), the mirror image of a person is a real-time avatar with the highest fidelity in terms of behavior and shape.

The origin of the word avatar in the context of virtual worlds dates back to 1979 when the term was first used in the computer game *Avatar* (Maggs et al., 1979). In 1980, the

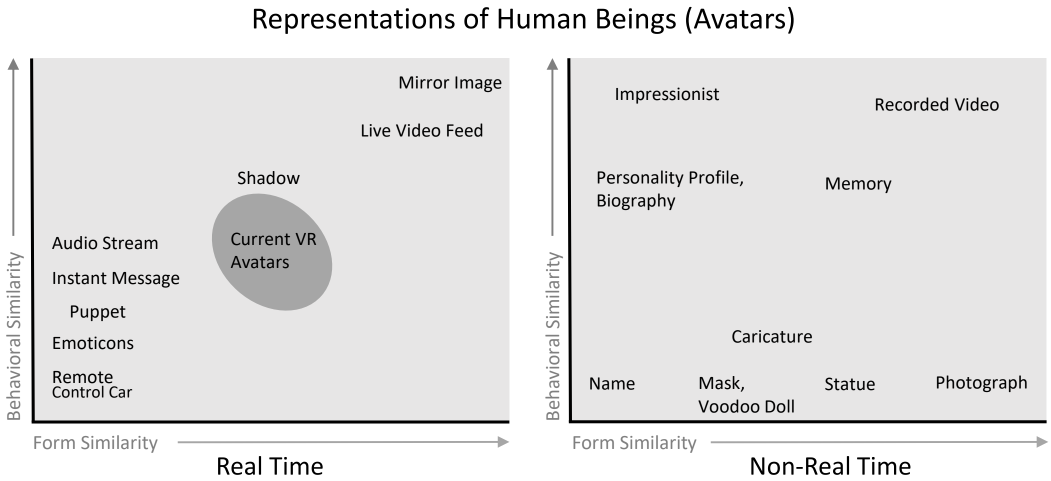

Figure 1.1: A framework by Yee (2007) depicting a variety of representations of human beings based on the two dimensions behavioral similarity and form similarity for real-time and non-real-time avatars. Due to the progress in technology and computing power since the creation of this framework in 2007, we argue that there is a positive shift of current VR avatars on both axes outperforming shadows in terms of form similarity. Illustration taken from Yee (2007).

author Norman Spinrad used the word avatar in his novel *Songs from the Stars* (Spinrad, 1980) to reference virtual entities in a computer-generated experience (Banks, 2018). The earliest use of the term to denote a digital entity symbolizing the user in virtual worlds was in 1985 in the computer game *Ultima IV: Quest of the Avatar* (Origin Systems, 1985). The same year, the online role-playing game *Habitat* (Lucasfilm, 1985) was released, which also coined the word avatar to refer to game characters. Banks (2018) mentions further occurrences in the cyberpunk novels *Neuromancer* (Gibson, 1984) and *Snow Crash* (Stephenson, 1992). Interestingly, besides the word avatar, the author of *Snow Crash* Neal Stephenson also coined the term “metaverse”, which has gained momentum recently and pushed the discussion about the successor of the internet (Ball, 2020; Sparkes, 2021). It describes a shared and persistent digital world as a virtual recreation of the real world people can inhabit and experience, and involves all modern media and technologies such as social media, VR and augmented reality (AR), as well as the internet.

Throughout the years, the term avatar has been explicitly used for a digital entity (e.g., a video game character) that represents and depicts the user (e.g., the player) in a virtual world (e.g., the in-game environment). Avatars, therefore, stand for a virtual embodiment of a user's self and manifest the user's existence in digital worlds. Seinfeld et al. (2021) introduced the concept of "User Representations", which integrates virtual characters as well as other virtual objects that extend the users' bodies allowing them to interact within digital worlds and perform actions. In this vein, by definition, a mouse cursor in a common graphical user interface of a desktop environment can also be considered an avatar. However, the term avatar typically refers to 2D or 3D characters that depict any kind of human, non-human, or fictional entity. Bailenson and Blascovich (2004) accordingly defined an avatar as "a perceptible digital representation whose behaviors reflect those executed, typically in real time, by a specific human being". Banks (2015) added that avatars function on behalf of a user resulting in a relationship between both of them. This notion illustrates the strong bond between user and avatar, which allows users to consider their digital counterpart as "themselves" instead of an "other" (Banks, 2015).

On the contrary, a digital character or object that depicts any kind of entity other than the user is commonly known as (virtual) *agent*. While an avatar is controlled by a user, agents are controlled by computer algorithms (Fox et al., 2015). Non-player characters (NPCs) in games, for example, are considered agents whereas the character of the player is denoted as the avatar. Another example for an agent is the popular Amazon's Alexa or Apple's Siri, which are both summarized as conversational agents as they pseudo-autonomously respond in a dialogue using human language without being controlled by a person (McTear et al., 2016).

In this thesis, we, therefore, use the term avatar to refer to any self-representation of the user in VEs. Virtual entities that are not controlled by users and do not represent them in VEs are considered agents. When using the term VR, we refer to immersive VEs that can be accessed via HMDs (stereoscopic displays) in contrast to "traditional" non-immersive environments using regular screens (monoscopic displays).

1.2 The Proteus Effect

In the following section, we introduce and define the Proteus effect, which originates from the avatar and its visual appearance. We refer to similar phenomena in the real world caused by the own appearance and learn about the etymology.

1.2.1 Summary

In his dissertation from 2007, Nick Yee reported a series of studies showing that avatars in VEs can change the behavior of users embodying them (Yee, 2007). The author observed that the avatars' visual appearance was responsible for such changes in behavior or attitude to occur. For instance, the attractiveness of an avatar affected the users' self-confidence in a dialogue in VR. Participants who experienced the virtual scenario from a first-person perspective in a more attractive avatar walked closer to the confederate in VR and were more extraverted during the conversation compared to an avatar that was perceived as less attractive. Similar phenomena were shown in a second study, where the avatars' height was manipulated (Yee & Bailenson, 2007). As body height is connected with attributes such as self-esteem and competence, users embodied in a taller avatar negotiated more confidently and aggressively in a bargaining task. These findings suggest that the avatar makes users (un)consciously behave in accordance with the expected behavior associated with its stereotypical appearance. Consequently, users conform to anticipated stereotypes and behave as they believe persons with such physical traits would behave and perform in such a situation. Alluding to the versatility of the God Proteus from Greek mythology, who was said to be able to change his shape at will, this phenomenon was termed the Proteus effect.

Consistent with the notion that attitudes and behavior depend on each other so that changes in behavior can be considered as an indirect outcome of a change in attitude (Clark, 2020), an avatar's attitudinal impact can also be attributed to the Proteus effect. Banakou et al. (2016), for example, documented that embodying a dark-skinned avatar can change the implicit racial bias toward dark-skinned people. Attitudinal changes could also be observed by Ahn et al. (2016), who showed that the embodiment of a coral during ocean acidification increased the users' connection to nature and raised awareness for environmental risks. These results suggest that an avatar's visual traits influence how users perceive the VE and interpret the events happening within the virtual world. As such, Banakou et al. (2013) also demonstrated that owning a virtual child body caused the users to overestimate object sizes.

In recent years, this phenomenon has been shown in a variety of different contexts and digital environments emphasizing its validity and efficacy (Ratan et al., 2019). Consequently, the Proteus effect evolved into a theoretical framework to explain behavioral, attitudinal, and perceptual changes caused by the mere visual appearance of avatars and the resulting stereotypical assessments of users embodying them. Hence, such changes originate from the embodiment of avatars with certain visual traits. Arguably, changes that are induced by other characteristics of avatars, such as their voice, facial expressions, animations, etc., can also be attributed to the Proteus effect (Ratan et al., 2019; Praetorius & Görlich, 2020). However, to learn about the effects of an avatar's visual appearance and isolate them from other confounding factors, the research in this thesis focuses on the mere visual characteristics to positively affect users during interaction in VR, e.g., body composition such as muscularity and athleticism or stereotypical appearances such as hairstyle, age, or attire.

1.2.2 Changing the Own Appearance

"Clothes make the man" (Latin *vestis virum facit*) is a Latin proverb coined by the Dutch philosopher and theologian Erasmus in his collection of Latin and Greek proverbs titled *Adagia* (Plural from Latin *adagium* "proverb") from the 16th century (Speake & Simpson, 2015, p. 55). This proverb means that people are judged and treated by others according to their clothes and their entire visual appearance. It illustrates that people can shape their social interaction with others by means of clothes, make-up, hairstyle, etc. Such minor changes of the own appearance are even considered socially desirable and are part of an everyday routine. Indeed, the way we dress and appear affects how other people perceive ourselves and behave towards us. Researchers found that students perceived their lecturers as more competent and professional when they wore formal clothes (e.g., business suits) but more interesting when they wore casual attire (Morris et al., 1996). Other scholars reported that applicants with masculine clothes during a job interview had a higher chance to become hired (Forsythe, 1990). Snyder et al. (1977) described a phenomenon known as behavioral confirmation that predicts that a person's behavior depends on the perception by others. The authors revealed the effects in a study investigating the communication during a telephone call. Male participants (referred to as perceivers) who believed that the female counterpart (referred to as the target) was attractive caused her to behave more friendly and likable compared to targets that were believed to be unattractive. Results indicate that the perception of others also affects the own behavior. The mutual influence of perceivers' and targets' beliefs and expectations can therefore evoke behavioral changes. Such findings corroborate Erasmus' words and suggest that others form an impression of someone based on the visual appearance. However, it is not only the other people who use such cues to derive how to behave toward someone. The *own* visual appearance also affects the *own* behavior and perception.

In line with the notion that wearing clothes represents a certain identity and appearance that make the wearer behave correspondingly (Stone, 1962), there is empirical evidence that professional hockey teams played more aggressively and received more penalties when wearing black jerseys than those that wore light-colored uniforms (Frank & Gilovich, 1988). As the color black is linked with aggression and evilness, researchers assume that the players unconsciously behaved in accordance to their jerseys. Adam and Galinsky (2012) also found that wearing a lab coat as a stereotypical attire of scientists and doctors increased cognitive performance during an attention-demanding task. The authors coined the term "enclothed cognition" in allusion to the psychological and philosophical theory of "embodied cognition", which claims that our perception and behavior highly depends on the characteristics of our body—a strong bond between body and mind (Aymerich-Franch, 2018). Hence, people can use their appearance to affect the way they perceive and interact with the surrounding environment. Apparently, a change in behavior caused by the own visual appearance is not an exclusively digital phenomenon as it also happens in the real world. However, our real physical body is bound to biological and physical laws that severely limit the possibilities of changing the own appearance. As previously mentioned, people can easily perform minor alterations through clothes, hairstyles, etc., to portray themselves in a certain way. Dieting, sports, or even plastic surgery allow for more significant transformations but require considerable time and are difficult to perform.

In the digital world, however, users can change their avatar's skin color, height, weight, age, gender, or human likeness within seconds. As digital environments allow to render and depict the avatar in any imaginable style, the way users are represented is therefore highly flexible and can be easily transformed into any possible appearance. In social media, for example, we can use photo editing (e.g., retouch, filters, etc.) to enhance our profile picture, which can be considered as our avatar in such applications. Virtual YouTubers can disguise their real identity using self-customized avatars that act as surrogates and deliver the live-streaming performance (Lu et al., 2021). The malleability of the users' self-representation in virtual worlds also opens up a lot of possibilities for researchers and designers to shape virtual experiences.

For years, game designers create avatars with certain characteristics to connect the players to the avatar and narrative and direct their intentions and actions within the game. For instance, game characters with a bulk, Hulk-like appearance and strong weapons are rather associated with aggressive behavior signifying the player to directly attack the enemies. On the contrary, slim and agile characters potentially prompt the player to sneak and silently eliminate enemies. Therefore, stereotypes are harnessed in the avatar creation process to provide a perceptible affordance intuitively informing the player about interaction strategies in games (Isbister, 2006, pp. 204–206). Similarly, heroes in games are typically attributed with attractive features (e.g., symmetrical face and body, healthy skin) as attractive people are perceived as warm, kind, sensitive, and successful. In contrast, villains can be designed with unattractive characteristics to elicit repulsive feelings in the player and create the appropriate mood in a game (Isbister, 2006, pp. 5–16).

On the one hand avatars with stereotypical appearances are promising for designers to implicitly communicate familiar concepts and ideas to users. As the game industry aims at designing their products for the global market to address as many users as possible and increase revenue, it seems plausible to equip game characters with stereotypical characteristics to instantly convey their roles within the game and create a connection with players. On the other hand findings from research suggest that stereotypes limit diversity and result in underrepresented groups and cultures (Banks, 2018; Isbister, 2006). Glaubke et al. (2001) reported that games frequently lack gender and racial diversity. The authors analyzed over 1000 games and documented that male characters were used almost four times more than female characters. In addition, the majority of game characters were White (56%) while Latinos (2%) and Native Americans (0.2%) only comprised a very small proportion. These findings are in line with results from recent studies critically discussing race and gender in games, and the oversimplification of cultural complexity (Passmore et al., 2017; Malkowski et al., 2017, pp. 109–129). To offer a more inclusive game experience and promote affinity and identification with game characters, some video games allow users to individually customize their avatar to design a certain version of their virtual character and express themselves. In *World of Warcraft* (Blizzard Entertainment, 2004), for example, which is one of the most popular massively multiplayer online games, players can choose the appearance, skills, and characteristics of their in-game characters. In the open-world role-playing game

Cyberpunk 2077 (CD Projekt RED, 2020), players can create their avatar using an extensive character creator editor that even offers to customize genitals and sexuality, which in turn affects the love story in the game.

Considering VR, an avatar acquires even greater significance as VR is capable of immersing users in a virtual world and creating the sensation of being surrounded by "another reality". As such, avatars do not only serve as a user interface between the real and the virtual world. In VR users can experience a sense of embodiment of the avatar that serves as a "new" body and represents their identity in VEs. Similar to the real world where our body acts as a reference frame and determines how we perceive the surrounding environment (Gibson, 1977), the avatar, therefore, influences how users perceive the VE and how they are perceived by other users sharing the same virtual space in collaborative virtual environments (CVEs). Guegan et al. (2016), for example, showed that avatars with stereotypical clothes worn by investors and scientists (e.g., lab coats) made the users embodying them more creative in a brainstorming task. This is further evidence that comparable mechanisms that apply in the real world also apply in virtual worlds. Similar to clothes in the real world, one might consider avatars as the users' "clothes" in the VE. However, as previously noted, VR serves a sheer endless amount of design choices to shape the avatar in any possible way. Hence, VR offers a high degree of flexibility of the own body in VEs which cannot be achieved by the way we dress and style ourselves in the real world. In line with Yee (2007), who stated that our "physical bodies are no longer the only bodies we can have", avatars are therefore more than our clothes in reality as they can be a tool to play games, extensions of our identity, or whole personality users can emotionally attach to in the digital world and beyond (Banks, 2015; Banks, 2018).

1.2.3 Etymology

For ages, the notion of being able to transform oneself into another shape has fascinated many cultures around the world. Hence, shapeshifting is a prevalent theme in many myths and legends, e.g, lycanthropes shift into werewolves in Europe, kitsune (foxes) from Japan or kelpies (water ghosts) from Scottland can shift into human beings, and Swan maiden from Norse folklore alters from human form into a swan (Sherman, 2015, pp. 411–412; Yee & Bailenson, 2007). One of the most influential epic poems is *Ovid's* masterpiece *Metamorphoses* (Anderson, 1997), which uses transformation as the unifying theme of all tales. In these tales, the Roman Gods typically transform themselves to utilize the characteristics of the new shape (e.g., Jupiter transformed into a beautiful white bull to seduce the God Europa) or punish humans by transforming them into animals or objects (e.g., Juno transformed Callisto into a horrible and ugly bear to avenge the affair with her consort Jupiter). The sea-god Proteus occurred in one of Ovid's stories: The God Menelaus witnessed that Proteus could transform into fire.

In Homer's *Odyssey*, Proteus was called the "Old Man of the Sea" who could foretell the future but only to those who were able to capture him (Homer & Murray, 1919). To avoid being captured and sharing his knowledge and wisdom with others, he transformed himself into a lion, a serpent, a pig, or even into the shape of water or fire. Consequently, the Proteus effect was named after the Greek sea god who could turn in any imaginable shape. According to the Oxford English Dictionary (n.d.), the adjective "protean" is derived from the polymorphism of Proteus and means "versatile" and "mutable" referring to one's ability to change and adapt rapidly and easily. This is in line with Lifton (1999), who coined the term "Protean self" to address the fast pace of our today's society and describe humans' ability to adapt to constantly developing and changing circumstances and situations in life.

In other domains such as medicine or biology, the term Proteus is used to highlight the variable characteristics of a disease or a living organism. There is a rare genetic disorder that makes patients suffer from an asymmetric growth of limbs (e.g., gigantism of hands or feet) or skin abnormalities (Bastos et al., 2008). To point out the highly morphologic variability of this disease, Wiedemann et al. (1983) named the disorder the Proteus syndrome. Bacteriologists called a specific genus of bacteria Proteus to highlight their variable cell length (Drzewiecka, 2016). Proteus is also a genus of an aquatic salamander called olm, which is also known as the "human fish" (Voituron et al., 2011). There is also a heavily cratered moon named Proteus orbiting the planet Neptune (Showalter et al., 2019).

1.3 Research Questions

The author identified three key topics that need to be addressed to gain a better knowledge about the virtual embodiment of avatars and how this knowledge can be applied to utilize the Proteus effect to improve performance in VR. Table 1.1 summarizes the topics and the corresponding research questions. In the following, the author outlines the research questions that were examined throughout the thesis.

Topic	No.	Research Question	Chapter
Body Ownership	RQ1	Does a RHI in the real world differ from a RHI in VR?	3, 4
	RQ2	Do virtual hands with missing fingers affect the behavior and experience in VR?	
Physical Performance	RQ3	Do muscular avatars affect the physical performance and perception of effort?	5
	RQ4	Do athletic avatars affect physiological responses to physical exertion?	
Cognitive Performance	RQ5	How does an Einstein avatar affect cognitive performance in CVEs?	6

Table 1.1: Summary of research questions of this thesis.

First, a foundational understanding of the underlying mechanisms of BOIs is required to be able to induce a sense of ownership of virtual avatars and, therefore, leverage their appearance to improve performance in VR. The topic *Body Ownership* refers to the fundamentals of body ownership of physical and virtual entities. To learn about the embodiment of avatars, we performed the seminal rubber hand illusion (RHI) in the real world as well as in VR, and also explored the conditions under which BOIs can and cannot occur in VEs. Additionally, we induced ownership of virtual hands in VR with altered body structures in terms of missing fingers to learn more about the effects of avatars with characteristics that strongly deviate from the users' physical self.

The topic *Physical Performance* builds upon the understanding gained from the topic *Body Ownership* and refers to the application of this knowledge to induce body ownership of avatars with different athletic appearances. We therefore aimed at leveraging muscular and athletic avatars to enhance the VR experience and make users perform better in physical tasks than they would in casual embodiments.

The topic *Cognitive Performance* explores whether the principles and effects from the topic *Physical Performance* translate to other virtual settings. Hence, we took advantage of stereotypical appearances using an Einstein avatar to improve the performance in cognitively demanding tasks in a multi-user setting.

1.4 Methodological Approach and Contributions

The research in this thesis followed a user-centered design approach. We first aimed at identifying and understanding a problem from a user perspective through a thorough literature review. In an ideation phase, we brainstormed different design solutions to solve the identified problem. Afterward, these concepts were translated into hard- and software prototypes, which were iteratively refined. In the evaluation phase, we then conducted user studies using controlled experiments in laboratory settings or in an online survey. We collected mainly quantitative data for hypothesis testing and gathered qualitative data to obtain valuable user feedback for improving our prototypes. To determine the effects of the independent variables, we took multiple objective and subjective measures using established quantitative methods. We then analyzed the data using well-established statistical tests.

According to the classification of research contributions in the field of HCI by Wobbrock and Kientz (2016), the thesis provides *empirical*, *theoretical*, and *artifact* contributions. The *empirical* contributions arose from five users studies conducted in this thesis. We learned about the fundamentals of BOIs by inducing them in the real world as well as in VR. We, therefore, learned how users react to the illusory sensation of embodying artificial limbs and bodies, and demonstrated perceptual, behavioral, and physiological responses. In a RHI experiment in the real world and in VR, we showed that the embodiment of a physical rubber hand resulted in similar and comparable effects as the embodiment of a virtual rubber hand (RQ1). This validates the usage of the RHI in VR and implies that the mechanisms during BOIs that apply for physical entities also apply for virtual entities.

We also investigated virtual hands with altered body structures in terms of missing fingers and different degrees of realism to understand how users respond to avatars with an appearance that strongly deviates from their own physical self (RQ2). We found that the removal of fingers could decrease the sense of presence and elicit negative emotional responses such as phantom pain. Such adverse effects were even larger at high levels of realism. We also found that users adapted their behavior during interaction in VR based on the visual appearance of the virtual hands. This contribution is relevant for designers of VR applications in general and avatars in particular, as it shows that negative perceptual and behavioral effects can occur when designing avatars with characteristics that strongly deviate from the users' physical body structures.

Based on this gained understanding and knowledge about BOIs, we then induced a sensation of owning avatars with appearances associated with high performance for improving physical and cognitive performance in VEs. In two studies, we reduced the perception of effort using athletic and muscular avatars during physical exertion in VR (RQ3). Additionally, we showed that athletic avatars can even decrease the heart rate (HR) while cycling in VR providing empirical evidence for the psychophysiological impact of avatars on users (RQ4). To find out whether the avatars' appearance can also affect cognitive performance in a CVE where two users are co-located, we leveraged an Einstein avatar to provide a virtual body that is associated with high cognitive competency (RQ5). We could not show effects on the users embodying Einstein. However, we showed that the other user performed better at a cognitively demanding task when he shared the virtual space with an Einstein avatar. As we learned in these studies how to design avatars to induce the Proteus effect to improve performance in VR, this thesis, therefore, provides *theoretical* contributions in terms of guidelines for the design and creation of virtual avatars in VR.

Finally, this thesis also provides *artifact* contributions. For the research in this thesis, we iteratively designed and developed different avatars and created immersive VR applications. We also shared the project files used in one study, which consist of the VR prototype and hand models[1]. Additionally, we built an experimental apparatus to systematically induce a RHI in the real world and in VR. A detailed description of this apparatus can be found in Chapter 3.

1.5 Publications and Work Distribution

The ideas, data, and findings of this thesis are mainly based on prior scientific publications that are listed in the following. Sections from papers that have been previously published are reprinted in this thesis. The personal contribution for each publication or currently unpublished manuscript is declared according to the CRediT taxonomy[2].

- **Utilizing the Proteus Effect to Improve Interactions using Full-Body Avatars in Virtual Reality (Kocur et al., 2019)**
  Some of the ideas for the studies in this thesis are based on this study proposal.

[1] `https://github.com/valentin-schwind/lessfingers-usage`
[2] `https://casrai.org/credit/`

The author wrote the article that was published at the *Mensch und Computer 2019 - Workshopband*.
Personal Contribution: Conceptualization, project administration, and writing the manuscript.

- **The Rubber Hand Illusion in Virtual Reality and the Real World - Comparable but Different (currently unpublished manuscript)**
  This manuscript is based on the Master thesis by Alexander Kalus. The student created the hard- and software prototype and collected the data. The author initiated and supervised the project. The author analyzed the data and wrote the paper using the valuable input by Niels Henze, Johanna Bogon, Valentin Schwind, and Christian Wolff. Chapter 3 is based on this manuscript that is currently under review.
  Personal Contribution: Conceptualization, data curation, formal analysis, contribution to methodology, project administration, supervision, validation, visualization, and writing the manuscript.

- **The Impact of Missing Fingers in Virtual Reality (Kocur et al., 2020b)**
  This publication is based on the Bachelor thesis by Sarah Graf. The student designed the software prototype for the study and collected the data. Valentin Schwind initiated and supervised the project. The author supported Valentin Schwind, who substantially contributed to drafting this manuscript. The article was published in the *26th ACM Symposium on Virtual Reality Software and Technology (VRST '20)*. Chapter 4 is based on this publication.
  Personal Contribution: Contribution to methodology, validation, visualization, and contribution to all parts of the manuscript.

- **Flexing Muscles in Virtual Reality: Effects of Avatars' Muscular Appearance on Physical Performance (Kocur et al., 2020c)**
  This publication is based on the Bachelor thesis by Melanie Kloss. The student created the prototype and collected the data. The author initiated and supervised the project. The author designed the 3D models of the avatars and analyzed the data. The author wrote the paper using the valuable by Niels Henze, Valentin Schwind, and Christian Wolff. The article was published in the *Proceedings of the 2020 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '20)*. Parts of Chapter 5 are based on this publication.

Personal Contribution: Conceptualization, data curation, formal analysis, contribution to methodology, project administration, supervision, validation, visualization, and writing the manuscript.

- **Physiological and Perceptual Responses to Athletic Avatars while Cycling in Virtual Reality (Kocur et al., 2021b)**
  This publication is based on the Master thesis by Florian Habler. The student was responsible for the design of the VE and collected the data. The author created the stimuli and initiated and supervised the project. The author analyzed the data and wrote the paper. Niels Henze, Valentin Schwind, Paweł Woźniak, and Christian Wolff contributed to the conceptualization of the study and supported the drafting of the manuscript. The article was published in the *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Parts of Chapter 5 are based on this publication.
  Personal Contribution: Conceptualization, data curation, formal analysis, contribution to methodology, project administration, supervision, validation, visualization, and writing the manuscript.

- **The Effects of Self- and External Perception of Avatars on Cognitive Task Performance in Virtual Reality (Kocur et al., 2020e)**
  This publication is based on the Bachelor thesis by Philipp Schauhuber. The student implemented the software prototype for the study, recruited the participants, and collected the data. The author initiated and supervised the project. The author designed the 3D models of the avatars and the VE. The author substantially contributed to drafting this manuscript and used the valuable feedback from Niels Henze, Valentin Schwind, and Christian Wolff. Data analysis was supported by the co-authors. The article was published in the *26th ACM Symposium on Virtual Reality Software and Technology (VRST '20)*. Chapter 6 is based on this publication.
  Personal Contribution: Conceptualization, data curation, formal analysis, contribution to methodology, project administration, supervision, validation, visualization, and writing the manuscript.

- **The Extent of the Proteus Effect as a Behavioral Measure for Assessing User Experience in Virtual Reality (Kocur et al., 2021c)**
  Parts of Section 7.3 are based on this position paper. The author wrote the article that was published at the *Workshop on Evaluating User Experiences in Mixed*

Reality of the 2021 CHI Conference on Human Factors in Computing Systems.
Personal Contribution: Conceptualization, project administration, and writing the manuscript.

- **Towards an Investigation of Avatars' Sweat Effects during Physical Exertion in Virtual Reality (Kocur et al., 2021d)**
  Parts of Section 7.4 are based on this study proposal. The author wrote the article using the valuable input by Valentin Schwind and Niels Henze. The article was published at the *Mensch und Computer 2021 - Workshopband*.
  Personal Contribution: Conceptualization, project administration, and writing the manuscript.

- **Towards an Investigation of Embodiment Time in Virtual Reality (Kocur et al., 2020d)**
  Parts of Section 7.4 are based on this study proposal. The author wrote the article that was published at the *Mensch und Computer 2020 - Workshopband*.
  Personal Contribution: Conceptualization, project administration, and writing the manuscript.

- The author was involved in further publications that are beyond the scope of this thesis. These publications address topics such as full-body game controllers (Schuhbauer et al., 2019) and fourth wall breaks in games (Kocur et al., 2021e), emotion in games (Halbhuber et al., 2019) and AR applications (Hartl et al., 2019), sentiment analysis in audiobooks (Ortloff et al., 2019), eye-tracking interfaces in VR games (Kocur et al., 2020a) as well as serious games to treat spider phobia (Wechsler et al., 2021), ethical considerations of VR (Dechant et al., 2020), education in HCI (Henze et al., 2020), and avatar therapies for depressive patients (Kocur et al., 2021a).

- The author was interviewed for newspapers and magazines that reported on findings of the studies presented in this thesis: ada magazine (2021-10-19), Popular Science (2021-11-16), c't magazine (2/2022), University of Regensburg Press (2021-12-10), Informationsdienst Wissenschaft (2021-12-10), Mittelbayerische Zeitung (2021-12-13), Bad Abbacher Kurier (2021-12-13), and Zeitschrift für Physiotherapeuten (2021-12-13).

1.6 Thesis Outline

In this thesis, we present the results and evaluations of five empirical studies, a review of related work, a discussion and summary of the findings, design implications as well as an outlook into future research directions. The work is structured as follows:

Chapter 1 - Introduction motivates the research in this thesis and presents the research questions and the author's personal contribution.

Chapter 2 - Background and Related Work summarizes previous work and presents explanations and theoretical frameworks for BOIs and the Proteus effect.

Chapter 3 - Understanding Body Ownership in Virtual Reality describes the results of a RHI experiment in the real world and in VR. The study was conducted to learn about the fundamentals of BOIs using the seminal RHI paradigm.

Chapter 4 - Effects of Altered Body Structures presents a study that explored how virtual avatar hands with altered body structures in terms of an abstract appearance and missing fingers affect the VR experience. This study was conducted to learn whether users accept virtual hands that strongly deviate from their own ones and how altered body structures influence behavior in VR.

Chapter 5 - Improving Physical Performance applies the knowledge from the previous chapters to induce a sense of body ownership of avatars with muscular and athletic appearances to improve physical performance in VR.

Chapter 6 - Improving Cognitive Performance presents one study that leverages an Einstein avatar to improve performance in cognitively demanding tasks in CVEs.

Chapter 7 - Conclusion summarizes the findings from previous chapters and presents design implications and directions for future research.

2

Background and Related Work

The research presented in this thesis is based on a growing body of work that demonstrated the Proteus effect caused by the embodiment of virtual avatars. To induce the Proteus effect using avatars, it is, therefore, vital to know how to elicit a feeling of owning an artificial body to make users perceive the avatar's body as their own one. Thus, it is important to learn about the cognitive principles underlying the sensation of having and owning a body. Hence, this chapter presents an overview of foundational research focusing on the concept of body ownership and perceptual illusions concerning the own body. This chapter starts with real-world experiments demonstrating that humans can experience artificial limbs and bodies as their own ones and presents the ways and methods to create such bodily illusions in the real world and in VR. We began to review the literature about body ownership and bodily illusions by searching academic databases such as Google Scholar, PubMed, or Research Gate using the terms "body ownership", "body ownership illusion", "rubber hand illusion", "virtual embodiment", and "avatar embodiment", and also combined them with the term "virtual reality". To learn the mechanisms underlying body ownership, we also focused on publications from disciplines such as cognitive psychology and neuroscience.

To learn about the Proteus effect, we queried the relevant research databases using the term "Proteus effect". We discarded results from medical and biological sciences that use the term Proteus to highlight the variable characteristics of cells or diseases. As the visual perception of a virtual avatar plays an important role during the Proteus effect, we aimed at gaining a deeper understanding of the process of perception in general and person perception in particular. We, therefore, searched for articles from social psychology researching stereotypes and human behavior (query: “person perception”, “social perception”, “stereotype perception”, “stereotype virtual reality”). We obtained additional insights into relevant concepts (e.g., mimicry, stereotype threat, etc.) that were further researched by querying the databases using the corresponding keywords. Hence, this chapter also presents the foundations of person perception and the important role of stereotypes. Finally, different theories explaining the Proteus effect are summarized, and related work that addresses this phenomenon in immersive and non-immersive VEs is presented.

2.1 Body Ownership Illusions

The human brain has the astonishing ability to resolve multisensory perceptual contradictions by producing illusions. This ability allows humans to perceive and experience the world in a way that does not match the physical reality. Even if we know that something cannot be real, we can still perceive it as such and behave correspondingly. Psychological research demonstrated numerous manifestations of intense perceptual illusions such as the seminal RHI. Botvinick and Cohen (1998) showed with the RHI that simultaneously stroking one’s hand while only seeing an artificial limb such as a rubber hand can make a person accept the artificial limb as one’s own. Researchers agree that the brain reacts to single information across multiple sensory cues from the same event by fusing them into a unified percept (Ernst & Banks, 2002; Hillis et al., 2002).

Even if there are apparent conflicts between vision (seeing the rubber hand being stroked), touch (feeling the stroking on one’s own hand), and proprioception (sensing the location of the own hand), the brain resolves these conflicts and creates a coherent and robust percept (Ernst & Bülthoff, 2004). Consequently, the brain produces the illusion that artificial limbs such as the rubber hand or even entire bodies can be accepted as the own ones. This illusion of perceived ownership of an artificial body is commonly known as the BOI. Hence, the plasticity of the brain’s body representation allows us to experience foreign limbs or bodies as if they were belonging to our own body. This is, thereby, an important factor why phenomena originating in body-related perceptual changes, such as the Proteus effect, can occur. In the context of HCI and VR, BOIs are commonly induced using avatars to provide the users with a virtual identity creating a vivid and lifelike experience. Beyond that, prior investigations found that the illusory ownership of an avatar is a significant moderator of the Proteus effect (see Section 2.3 for a detailed description of the determinants of the Proteus effect). Consequently, it is important to know how to design appropriate avatars to be able to induce a strong BOI to leverage the Proteus effect in an optimized way. This necessitates a deeper understanding of the cognitive processes underlying BOIs. Hereafter, we discuss the theoretical approaches regarding the cognitive processes behind induced BOIs and present previous work that addresses this phenomenon in real-world settings and VEs.

2.1.1 Cognitive Mechanisms

To understand the cognitive mechanisms underlying BOIs, it is important to know how the brain can even create a sensation of "owning" a body. Roth and Latoschik (2020) considered different definitions of body ownership. The authors summarized them as "the experience and allocation of a bodily self as one's own body, as 'my body', the particular perception of one's own body as the source of bodily sensations, unique to oneself so that it is present in one's mental life" (Roth & Latoschik, 2020, p. 3547). Accordingly, Waldenfels (2004) discussed "the riddle about our body" by raising the question how one knows that a certain body is indeed the own body. The crucial difference between how we perceive our own body in contrast to a foreign body or any other external object in the environment is that, in the case of our body, the brain can access sensory information which is not accessible for any other external entities (Kilteni et al., 2015). Consequently, the brain can distinguish between the own body and other bodies or external objects. As there is no "sixth" sense responsible for establishing a body ownership, the brain has to rely on the incoming sensory information to determine which body is owned at any point in time. In turn, this lack of such a "sixth" sense is indicated through BOIs, which demonstrate that the brain's perception of what is and what belongs to the own body can be manipulated through conflicting sensory information from different modalities.

Botvinick and Cohen (1998) ignited the research interest in BOIs with the seminal RHI, which has evolved into an established experimental paradigm across various fields to investigate human cognition (Moseley et al., 2012). Despite existing variations in the experimental procedure (Riemer et al., 2019), typically, the participants sit on a chair seeing a rubber hand placed on a table directly in front of them in an anatomically plausible position. They cannot see their real hand, which is occluded and located next to the rubber hand. To induce the illusion of accepting the rubber hand as part of the own body, a multisensory conflict using visuo-tactile synchrony is created. The rubber hand as well as the participants' real hand are being stroked synchronously so that the participants have tactile sensations originating from the real hand but see the stroking on the rubber hand. As the brain aims at maintaining integrity of incoming sensory signals to be able to create a consistent and coherent representation of the body and the surrounding environment, it resolves this perceptual conflict by shifting the spatial location of the real hand towards the location of the visual percept (Tsakiris, 2010; Moseley et al., 2012). This illusory shift towards the artificial hand is commonly known as the proprioceptive drift, which is frequently used as an objective measure for quantifying the induced RHI (Riemer et al., 2019). As vision is presumed to be the most dominant sense with higher reliability and acuity than senses like touch and proprioception, the brain ascribes greater significance to the visual perception and eventually incorporates the rubber hand into the own body representation (Armel & Ramachandran, 2003). Consequently, the participants experience this prosthetic limb as part of their own body. This illusory sensation is frequently assessed through questionnaires, behavioral correlates such as the aforementioned proprioceptive drift, or physiological responses such as increased electrodermal activity or HR as a consequence of a perceived threat to the rubber hand (Riemer et al., 2019).

Botvinick and Cohen (1998) proposed that the RHI is based on bottom-up processing of incoming sensory information. They found that this illusion necessitates visuo-tactile synchrony, as an asynchronous stimulation, e.g., visual stimulation precedes tactile stimulation (Tsakiris & Haggard, 2005), could not produce this illusory sensation. This is in line with Armel and Ramachandran (2003), who showed that the brain can even incorporate a table into the own body representation when synchronous visuo-tactile stimulation is applied (Ramachandran & Rogers-Ramachandran, 2000). As it is absurd that something like a table can be accepted as part of the own body and contradicts any physical and biological laws, researchers assume that the overall percept is, therefore, created in a bottom-up fashion by the fusion of single information across multiple sensory cues (Hillis et al., 2002). Armel and Ramachandran (2003) argue that the illusion emerges from Bayesian logic underlying all human perceptual processes. Even if there are apparent discrepancies and we know that something is absurd and cannot be real, our brain resolves these discrepancies in a statistically optimal fashion to generate a useful hypothesis about the own body and the world (Ernst & Bülthoff, 2004). The brain detects statistical correlations between the single incoming sensory information from different modalities and integrates them into a fused overall percept regardless of its logical plausability (Armel & Ramachandran, 2003). Examples such as the "invisible hand illusion" indicating that one can experience a sense of embodiment of an empty space during synchronous visuo-tactile stimulation confirm the notion that BOIs are mainly stimulus-driven resulting from the statistical integration of single cues (Guterstam et al., 2013; Armel & Ramachandran, 2003). These correlations between the input of different sensory modalities are both necessary and sufficient for inducing BOIs (Tsakiris, 2010).

Many researchers, however, disagree that BOIs can be explained without considering top-down mechanisms such as expectations, prior knowledge, and contextual information, e.g., the visual appearance of the stimulus (Litwin, 2020). If it was indeed sufficient to use spatiotemporal multisensory stimulation for inducing a BOI, then one could experience potentially any kind of body or object as one's own. Despite the findings that we can experience an "invisible hand illusion" or a table as part of the own body, researchers assume that certain requirements regarding higher-order body representations have to be met for BOIs to occur. Kilteni et al. (2015) concluded that semantic information provided by the to-be-embodied entity strongly modulates or even extinguishes the BOI. For example, the visual resemblance between the to-be-embodied entity and the real body parts significantly affects the extent of the BOI. Non-corporeal objects that violate human anatomical structures, e.g., checkerboards (Zopf et al., 2010) or wooden blocks (Tsakiris et al., 2010), cannot induce a BOI. In this vein, virtual bodies with a very low biological realism also negatively affect the strength of the experienced body ownership (Maselli & Slater, 2013). Similar results were found when the anatomical posture of the rubber hand was incongruent with one's real hand posture, e.g., a postural mismatch created using a rotated rubber hand (Costantini & Haggard, 2007). Likewise, Lloyd (2007) showed that the rubber hand has to be located within the peripersonal space—the region immediately surrounding the body where objects can be reached—with a distance to the real hand not exceeding 30 cm. As the human body changes across the life span, Marotta et al. (2018) assumes that one's age also modulates the extent of BOIs. With this in mind, individual differences in general, such as personality traits (Dewez et al., 2019; Marotta et al., 2016), have to be considered when inducing BOIs. Overall, these results suggest that the to-be-embodied entities need to satisfy to some extent semantic constraints while the exact boundaries of tolerable violations are unknown yet (Kilteni et al., 2015).

To take account for semantic information as moderators of BOIs, Tsakiris (2010) proposed a neurocognitive model to explain the underlying processes, which consists of three critical comparisons. First, the visual appearance and shape of the to-be-embodied entity are subconsciously compared against a pre-existing internal body model representing the properties of the own body, e.g., visual and structural characteristics. If the characteristics of the to-be-embodied entity fit the body model and pass the first test, the second comparison between the current state of the body and the anatomical and postural characteristics of the to-be-embodied entity occurs. Similarly, this second test has to be passed, e.g., congruent postural features of a rubber hand and the real hand. The third comparison is between the incoming sensory information. A conflict between the sensory input, e.g., visual and tactile, is resolved by recalibrating the visual and tactile coordinate systems resulting in a subjective experience of body ownership, which eventually updates the internal body model.

A further approach was described by Kilteni et al. (2015) who used the predictive coding framework to explain the cognitive mechanisms during BOIs. Predictive coding postulates that the brain makes predictions based on the incoming sensory information and the elicited associations. To reduce the prediction error, the brain produces a perceptual illusion aiming at creating a coherent and consistent representation of the body and the surrounding environment, e.g., shifting the spatial position of the real hand towards a rubber hand. Therefore, it generates a "best guess" and even updates prior knowledge and beliefs to a certain extent to satisfy this perceptual estimate. Previous studies, for example, showed that even autonomic functions, such as thermoregulation (Moseley et al., 2008) or the immune system (Barnsley et al., 2011), can be affected through these neural processes in the brain during bodily illusions. As such, Moseley et al. (2008) found that the skin temperature of the real hand decreased when the participants experienced a prosthetic counterpart as part of their own body. As this drop in skin temperature could only be observed in the real hand, not in other body parts, the authors, therefore, assumed that the real hand was "disowned" and replaced by the artificial hand. This process of "disownership" was explained through a so-called "cortical body matrix" (Moseley et al., 2012). Moseley et al. (2012) introduced the "cortical body matrix" as a neural representation involving the body, the personal space, and the peripersonal space (near surrounding space around the body), which aims at maintaining the integrity of the body in a psychological and homeostatic way. Through visuo-tactile stimulation, the neural areas associated with the space occupied by the rubber hand increase their activity starting to incorporate it into the own body schema, which in turn results in the sensation of the rubber hand being one's own. On the contrary, the neural areas associated with the space around the real hand decrease their activity, which in turn results in decreased homeostatic controls and sensory processing and, finally, in a "disownership" of the real hand (Moseley et al., 2012). In line with this notion, Llobera et al. (2013) found a decreased temperature sensitivity in the real hand while embodying a virtual avatar in VR. The authors explained that "when the body appears to have changed, and when the evidence of this change is provided through consistent multisensory data pointing to a new interpretation of body structure, then the body matrix propagates the change to all levels—perceptual, cognitive, personal, and peripersonal space, regulatory function, and protection mechanisms" (Llobera et al., 2013). However, many other studies were not able to replicate these and other related results using the RHI paradigm (de Haan et al., 2017; Rohde et al., 2013; Guterstam et al., 2011; Schütz-Bosbach et al., 2009; Folegatti et al., 2009; Llobera et al., 2013; Campos et al., 2018). For this reason, effects on skin temperature caused by the RHI are highly controversial (de Haan et al., 2017).

Although the precise mechanisms underlying BOIs are yet not fully clarified, these models and frameworks provide important insights into the fascinating ability of the brain and its high malleability. Even the representation of a human body, which should be actually robust and constant considering the amount of time we perceive ourselves in daily lives, can be altered instantly in a significant way.

2.1.2 Full-Body Illusions in Virtual Reality

Rapid advances in VR technology enable researchers to use perceptual conflicts in VR to learn about human cognition and cognitive processes of limb integration. Thus, researchers and designers of VR applications have recognized the potential of BOIs induced in experiments from the real world and, therefore, have taken advantage of the malleability of the brain's body representation to create immersive VR experiences. To establish the sense of having an own body in VEs, researchers and designers commonly use avatars. In line with results from real-world experiments, previous work found that a first-person perspective—perceiving the virtual world through the eyes of the avatar—in combination with congruent stimulation of different sensory modalities could create such strong cues, that users have the feeling of embodying avatars and accepting them as their virtual alter ego (Kilteni et al., 2015; Waltemate et al., 2018; Dewez et al., 2021).

According to real-world settings, similar constraints have to be satisfied to be able to induce the feeling of ownership of the avatar, such as a first-person perspective, congruent multisensory stimulation, and anatomical plausibility (Kilteni et al., 2015).

Essentially, VR allows creating experiences that are hardly feasible or impossible to create in real-world settings. For example, researchers do not have to rely on "passive" visuo-tactile synchrony but instead, they can use other types of multisensory correlations to invoke bodily illusions. Through tracking devices or modern motion capture technologies, the users' motion can be registered and transferred onto the virtual skeleton of the avatar resulting in a visuo-motor synchrony—a synchrony between movements of the real body and the virtual body. Sanchez-Vives et al. (2010), for example, could induce a virtual RHI by visuo-motor synchrony without tactile stimulation. In their experiment, the participants could move their real hand and fingers and could see the virtual hand reacting synchronously. Kokkinara and Slater (2014) also showed that users can experience a virtual leg as their own and that visuo-motor correlations can induce stronger limb ownership than visuo-tactile cues. Researchers assume that through visuo-motor synchrony the users experience a sense of agency over the artificial limb—the sensation of causing and controlling one's own body movements—amplifying the experienced body ownership of the avatar (Roth & Latoschik, 2020; Braun et al., 2018).

Even full-body illusions can be invoked when users can move their entire body and the avatar simultaneously "mimics" these motions in real time. Banakou et al. (2018), for example, showed that users can have the sensation of embodying an entire foreign body while experiencing visuo-motor synchrony. The users perceived the VE from a first-person perspective and their real body was spatially substituted by the avatar's body. When they looked down at their own body, they saw the virtual avatar's body instead (Banakou et al., 2018). Even if visuo-tactile correlations can trigger ownership sensations of avatars, visuo-motor synchrony can provide such strong cues so that intense full-body illusions can be induced through VR systems (Banakou et al., 2013; Banakou et al., 2016; Waltemate et al., 2018; Schwind et al., 2017b; Maselli & Slater, 2013). Beyond that, VR serves an extended design space: The avatar can be rendered in any desired style allowing the user to embody any possible appearance. Previous work found that users could even accept virtual bodies with visual characteristics that strongly deviate from the own physical self, e.g., avatars that indicated having a different gender (Slater et al., 2010; Schwind et al., 2017b) or physical constitution (Normand et al., 2011), being much younger (Banakou et al., 2013) or older (Banakou et al., 2018), or having a different skin color (Peck et al., 2013; Hasler et al., 2017; Banakou et al., 2016). Despite avatars' characteristics fundamentally different from the users' real ones, researchers assume that the applied visuo-motor synchrony combined with a human body shape of the avatar seems to saturate the bodily illusion so that textural differences cannot prevent the illusion from occurring (Kilteni et al., 2015).

That being the case, the term "homuncular flexibility" was coined by Lanier (2006), which describes the users' ability to adapt to virtual bodies with altered body structures. "Homuncular" refers to the distorted visualization of the human body within the brain commonly known as the cortical homunculus (Penfield & Boldrey, 1937). The basic idea behind this well-known visualization is that those body areas that contain more nerve cells than others occupy more space in the corresponding brain area resulting in a neurological map accordingly representing the parts of the human body in the brain. Research from cognitive neuroscience investigating phantom limb pain showed that this cortical map is highly plastic. Ramachandran and Hirstein (1998), for example, found that touching certain face regions of arm amputees made them feel being touched on the phantom digits. The authors explained this with a sensory reorganization in the brain so that the nerve cells representing the amputated hand area were getting activated when certain face regions were tactilely stimulated. As both brain areas corresponding to the face and the hand are adjacent according to the cortical homunculus, the cortical area for the hand is captured by the sensory input from the face (Ramachandran & Hirstein, 1998).

These results from real-world phenomena provide evidence for the "homuncular flexibility", which was confirmed in studies conducted in VR. In contrast to removing limbs, previous work found that users can even accept supernumerary limbs such as a third arm (Won et al., 2015) or a sixth finger (Hoyet et al., 2016) as own ones learning to use them after an adaptation phase. Despite such structural differences, results imply that users can rapidly adapt to the visual appearance of avatars. However, as previously mentioned, it is to note that the exact boundaries to what extent body structures of the virtual avatar may differ from the users' real ones without deteriorating the VR experience remain unclear. In this vein, Gonzalez-Franco and Lanier (2017) concluded that the brain rejects an illusion when the discrepancy between the sensory inputs across different modalities and the brain's predicted state becomes too extreme. Consequently, more research is needed to explore when the discrepancy is “too extreme” to gain a deeper knowledge about the brain’s plasticity and the consequences for the design of avatars in VR.

From an HCI perspective, these bodily illusions can be used to create vivid and immersive VR experiences. Previous work found, for example, that having a body in VR in terms of an avatar can increase the sense of presence (Baylor, 2009; Usoh et al., 1999; Slater et al., 1995; Steed et al., 2016a; Witmer & Singer, 1998)—an important characteristic and quality attribute of VR describing the feeling of being or acting in the VE even when being physically situated in another place (Slater, 2018). This phenomenon is accordingly described as the “place illusion” (Slater, 2009). When owning a virtual avatar in VR, the events happening to the avatar are related to the users as they “virtually” are the avatar. Thus, users act and respond to the events in the VE as if they were real and happening to them (Slater et al., 2009). This phenomenon is termed the “plausibility illusion” (Slater, 2009). In contrast, having no body in VR can create the impression of being an observer rather than a direct participant.

Similarly, it has been shown that the usage of avatars can enhance users’ depth perception (Ebrahimi et al., 2018) as the virtual body provides evident cues about the users’ location and their limb positions (Steed et al., 2016b). Slater and Wilbur (1997) recognized that VR requires a virtual body, which “represents the being that is doing the perceiving” from an egocentric viewpoint, to enable users experiencing a sense of presence. Accordingly, in CVEs where multiple users share the same virtual space, the avatar is the central identity cue of a user affecting social behavior and interaction, e.g., interpersonal distance (Sanz et al., 2015) or self-disclosure (Yee, 2007). It is therefore recommended to provide users with a digital body to let them experience the virtual world naturally and realistically as they would with their real physical body. However, it is essential to consider the challenges that come along with designing avatars for immersive VEs, e.g., the prominent uncanny valley (Mori, 1970). Particularly when creating realistic and anthropomorphic avatars, minor imperfections can elicit eerie and repulsive feelings deteriorating the extent of the body ownership of the avatars and the overall user experience (Lugrin et al., 2015; Gorisse et al., 2019). As a consequence, Schwind et al. (2018b) provided design guidelines to avoid the uncanny valley, e.g., avoiding visual-haptic mismatches or gender swaps.

2.2 Theoretical Foundations of the Proteus Effect

The Proteus effect describes behavioral, attitudinal, and perceptual changes due to the users' stereotypical assessments of an avatar's visual appearance. To be able to leverage this phenomenon and use it in an optimized way to improve user performance in VR, it is crucial to understand why it occurs and how the visual characteristics of an avatar can affect the user in the intended ways. Several psychological theories underlying the Proteus effect are debated, which describe the cognitive mechanisms responsible for this phenomenon. To identify and derive the underlying mechanisms, we broke down the complexity of the Proteus effect and disassembled it into its single events occurring during this phenomenon. We argue that the Proteus effect consists of three events: (1) perceiving an avatar, (2) experiencing a change in self-perception, and (3) changing the behavior, attitude, and perception. We assume that, first of all, users perceive a virtual character without the conscious sensation that they control or embody it, as it takes some time until they feel a sense of ownership (1). After this short period of time, e.g., an embodiment phase for inducing a BOI, users then experience the virtual character as their own body, as it, for example, reacts to their motion or controller input creating a sense of agency and ownership. This, in turn, causes users to experience a change in self-perception (2). Finally, the combination of both precedent events can trigger changes in users' behavior, attitude, and perception (3).

Although current VEs are yet far away from being indistinguishable from the real world, they still make users realistically respond to the presented stimuli so that they behave as they would in corresponding real-world scenarios. Insko (2003) described an example: If a virtual ball is thrown at the users' head and the users react to this threat by ducking, then we would assume that they feel present in the VE and have a realistic experience. Hence, the VE is being processed in the brain as if it was real. The same applies to an avatar, which is processed in the brain like "me" or "my body", or other virtual agents sharing the same virtual space, which are considered as "other people". We, therefore, examined this effect in the context of theoretical developments in cognitive and social psychology, as the underlying mechanisms of the Proteus effect are not novel phenomena. We argue that they can be explained with the existing knowledge about the cognitive processes activated when we perceive ourselves and others, and how this can affect our behavior, attitude, and perception. Inspired by the seminal work about the Proteus effect by Yee (2007) and other studies demonstrating evidence for this phenomenon, we identified several relevant psychological processes underlying these three events that are related to self-perception, priming, stereotyping, person perception, embodied cognition, and mimicry. In the following section, we present different psychological explanations and theories for this phenomenon and discuss them based on findings from previous work.

2.2.1 Self-Perception Theory

One potential explanation for the Proteus effect is rooted in self-perception theory. According to Bem (1972), self-perception theory posits that people observe themselves from an imaginary third-person perspective similarly to an external observer to understand why they behave in a certain way. Just as we consciously or unconsciously observe others' behavior in our daily lives to evaluate them and infer their attitudes and feelings as causes for their actions, Bem (1972) argued that humans also analyze their own behavior to derive their own attitudes and emotions. This process is called self-attribution and is based on the notion that our internal states, e.g., emotions or attitudes, are rather weak and ambiguous that is why we rely upon our own external cues such as the behavior or appearance to understand what we are feeling and what may have caused our actions. Researchers assume that there is basically no fundamental difference in the way people interpret their own and other people's behavior.

Lepper et al. (1973), for example, showed that children, who liked drawing and received an extrinsic reward for a drawing task were less interested in drawing afterward compared to children who did not receive a reward. The authors argue that this counter-intuitive self-perception effect is based on the fact that we evaluate our behavior in the same manner as how we think others would evaluate it. In this case, others would assess that the children drew because they were driven by the reward rather than pleasure and fun and, therefore, the children inferred that drawing was less interesting and enjoyable to them. Another example for a self-perception process is shown by Kellerman and Laird (1982), who found that participants believed that their cognitive performance was better when wearing eyeglasses although there was no difference in the actual performance. As the stereotype of smart and intelligent people wearing glasses was activated, they accordingly described themselves as more competent when wearing glasses (Kwon, 1994).

To transfer this idea to avatars and the Proteus effect, Yee (2007), for example, showed that users who were embodied in attractive avatars behaved more confidently in terms of interpersonal distance and self-disclosure in a dialogue in VR compared to being embodied in non-attractive avatars. The users connected the attractiveness of their avatars with attitudes such as self-confidence and extraversion, and, therefore, behaved consistently with their associations elicited by the avatars. The authors showed similar results in a second experiment where they manipulated the height of avatars as height is associated with self-esteem and competence. In a VR bargaining task, participants embodied in taller avatars behaved more confidently and performed better in negotiation (Yee et al., 2009).

In a meta-analysis about the Proteus effect, Ratan et al. (2019) documented that this phenomenon has been found in various contexts with different outcomes, e.g., dating partner choices (Yee & Bailenson, 2009), consumer behavior (Ahn & Bailenson, 2011), food choice (Sah et al., 2017), or cognitive performance (Ratan & Sah, 2015). Self-perception theory is frequently used as a framework to explain the Proteus effect and its underlying mechanisms. However, Ratan et al. (2019) discussed further psychological theories and argued that additional mechanisms such as priming contribute to the effects of avatars on users and, therefore, have to be considered to understand the phenomenon in its entirety.

2.2.2 Priming

Peña et al. (2009) conceived the Proteus effect as a consequence of priming mechanisms. The authors showed that users controlling avatars with a dark robe in a non-immersive VE tended to behave more aggressively and antisocially compared to users with avatars in white robes. In line with Frank and Gilovich (1988), who conducted a similar experiment in a real-world setting, the users associated aggression and toughness with black clothes resulting in the predicted behavioral changes. However, the authors argue that the effects were caused by priming based on the automaticity model instead of self-perception. The automaticity model postulates that situational cues can prime individuals without them being aware of it (Bargh & Chartrand, 1999). This means that the perception of certain cues makes individuals automatically and unconsciously adapt their behavior or thinking to act in a way consistent with the cues and their triggered associations. Bargh et al. (2001), for example, found that participants who were primed with words related to success and high performance, e.g., win, succeed, or master, performed better in a cognitive task compared to participants who were exposed to neutral worlds. Similarly, the black-colored robes of the avatars were situational cues, which activated related concepts, e.g., aggression, and obstructed inconsistent concepts, e.g., kindness (Peña et al., 2009; Dijksterhuis & van Knippenberg, 1996). In contrast to self-perception theory where the avatar induces behavioral and attitudinal changes due to its visual appearance, priming does not result from changes in a user's self-perception through the embodied avatar. Priming encompasses any situational cues, e.g., the VE, the events, or other external cues, which affect the users and their behavior or attitude. Likewise, Peña et al. (2009) found in a second experiment that participants controlling an avatar from a third-person perspective associated with the Ku Klux Klan were more aggressive (i.e., activating related concepts such as aggression) and less affiliative (i.e., inhibiting inconsistent concepts such as affiliation) compared to avatars dressed as doctors. As these twofold effects are attributed to priming mechanisms (unconscious behavioral adaptation) caused by the mere presence of the avatar and not by changes in self-perception (conscious behavioral adaptation), they, therefore, concluded that the Proteus effect may be explained by priming rather than self-perception theory. However, if this assumption was true, this would mean that there is no "difference between being and seeing" (Yee & Bailenson, 2009), or in other words, between embodying an avatar and seeing an agent.

To verify this hypothesis, Yee and Bailenson (2009) investigated whether the Proteus effect depends on the embodiment of the avatar. They found that the extent of behavioral changes was higher when being embodied in an attractive avatar compared to observing an attractive agent. These results suggest that there is a conceptual difference between effects caused by priming through the mere observation of visual stimuli and the effects caused by the embodiment of avatars with certain identity cues. Accordingly, Osimo et al. (2015) showed that avatars had a stronger cognitive impact when moving synchronously with the embodying user than when moving asynchronously. This was confirmed by Banakou et al. (2013), who documented that visuo-motor asynchrony can reduce and even extinguish the Proteus effect. In their study, participants tended to overestimate object sizes while embodying a virtual child. However, this effect could only be shown for participants who embodied avatars with child-like attributes who reacted synchronously to the embodying users' movements. Nonetheless, these findings do not allow us to ultimately determine whether the Proteus effect is driven either by priming, self-perception, or even the interplay of both concepts. Consequently, Ratan and Dawson (2015) proposed that both, self-perception and priming, contribute to the Proteus effect.

2.2.3 Self-Perception and Priming

Ratan and Dawson (2015) reconciled both explanations for the Proteus effect arguing that effects caused by self-perception do not rule out priming mechanisms and vice versa. Basically, they hypothesize that by embodying an avatar the user's cognitive schema of the avatar-related concepts is connected with the cognitive schema of the user's self-related concepts, so that the priming of one schema can activate the other. The authors noted that their approach to explain the Proteus effect should not be a new third theory but rather serve as a middle ground connecting the aspects of both perspectives (Ratan et al., 2019).

To explain their approach in detail, we decompose the psychological process according to Ratan and Dawson (2015) based on an example: Banakou et al. (2018) found that embodying Albert Einstein as a stereotype for superior intelligence improved performance in a cognitive task. In accordance with self-perception theory, the users perceived themselves through an imaginary third-person perspective to derive how they should act and behave. As they observe Einstein as their "new" bodily self, stereotypical characteristics associated with the avatar, such as intelligence, competence, and high cognitive abilities, were activated. Consequently, they inferred "I am Einstein" and concluded "I am very intelligent". Additionally, the users' self-related concepts should also be activated (Ratan & Dawson, 2015). As Banakou et al. (2018) found that self-esteem is a moderator of the effects on cognitive performance caused by the Einstein avatar, concepts related to self-esteem such as pride, satisfaction, and other attitudes towards oneself could have potentially been activated. Overall, both sets of cognitive schema were primed and linked, e.g., "I am very intelligent" related to the Einstein avatar and "I am proud of myself" related to the user, and, thereby, resulting in behavioral changes. Both sets could augment or decrease the extent of the induced changes.

We assume that the participants consciously or unconsciously regulated their behavior, e.g., in terms of the cognitive effort they put into the task, as it seems impossible that a temporary change of the users' self-representation can improve their actual cognitive abilities. Consequently, they try to conform to the anticipated stereotype of Einstein and behave as they think Einstein or a person with exceptional intelligence would behave and perform in such a scenario. Thus, the induced behavioral changes, e.g., in terms of cognitive effort, resulting from changes in self-perception and priming mechanisms could in turn affect the cognitive performance.

Further evidence for the Proteus effect was found by Banakou et al. (2016), who have documented that the embodiment of dark-skinned avatars by light-skinned participants reduced implicit racial bias assessed through the Implicit Association Test (IAT; Greenwald et al., 1998). Even if the authors did not mention that the Proteus effect was responsible for such effects to occur, they explained their findings in line with self-perception mechanisms and the activation of self-related concepts. The IAT is a statistical measure of stereotypical associations between categories, e.g., the ethnic classification "Black" and negative categories such as "aggressive" or "violent" (Yang et al., 2014). As the users embodied black avatars and virtually "transformed" into them, their own set of self-related categories then disrupted the associations between categories. As it is assumed that users likely have more positive associations with themselves, the stereotypical associations between "Black" and "negative" were confounded by elicited positive associations connected with themselves, which then resulted in reduced IAT scores indicating a lower racial bias (Maister et al., 2015).

2.2.4 Stereotype Activation during Person Perception

Another important concept related to the Proteus effect is the activation of stereotypes—positive, negative, or neutral "cognitive structure[s] containing the perceiver's knowledge and beliefs about a social group and its members" (Hamilton et al., 1990). In contrast to the individuation of a person, for example, where a perceiver focuses on a person's specific details, stereotyping describes categorical thinking by assigning people to certain categories (Macrae et al., 1994). Researchers distinguish between two types of stereotypes: in-here and out-there stereotypes (Kowert et al., 2012). The former represents personal beliefs whereas the latter beliefs that are held by a wider population. Clark (2020) formulated a question in two different ways to clarify the difference: "How likely do you believe it is that a larger-bodied person is lazy" referring to in-here stereotypes, versus, "How likely does an average person believe it is that a larger-bodied person is lazy" referring to out-there stereotypes. Researchers assume that the process of stereotyping is an evolutionary mechanism that allows humans to be able to process the huge amount of information encountered daily. This ability to acquire stereotypes constructed from our personal or other's experiences and opinions, and to socially categorize others enables us to simplify the complexity of our social world and save valuable cognitive resources (Macrae & Bodenhausen, 2000). These residual cognitive resources can then be used to direct our attention towards other concerns (Sherman et al., 1998).

Social psychologists assume that stereotyping is deeply rooted in every human being without being able to avoid the activation of stereotypes when encountering others (Devine, 1989). Therefore, Devine (1989) denoted the activation of stereotypes as "inescapable". As human societies, for example, have always competed for limited resources, it is considered natural to distinguish between "friend and foe". The development of biased preferences and stereotypes makes us behave in ways in favor of people belonging to the same group compared to people from another group, e.g., regarding ethnicity, gender, or religion (Fiske, 2015). Not being able to avoid the activation of stereotypes does not mean that we cannot actively stop unwanted thoughts and thereby counteract biased categorization (Macrae & Bodenhausen, 2000). However, this counteractive process is deemed as very effortful and cognitively demanding (Wegner, 1994; Bargh, 1999). Particularly in situations where we have exhausted cognitive resources and limited knowledge about someone or something, we tend to automatically apply stereotypes as "cognitive shortcuts" (Todd & Gigerenzer, 2000) for the sake of efficiency (Sherman et al., 1998; Todd & Gigerenzer, 2000; Devine, 1989). Macrae et al. (1994) denoted stereotypes as "energy-saving devices" by showing a performance enhancement through the activation of a stereotype while multitasking. As the participants employed the activated stereotype to efficiently form an impression of a target person, the saved cognitive resources could be used to listen carefully to a tape recording and, therefore, memorize the provided information more effectively (Macrae et al., 1994).

During the Proteus effect, we assume that a natural person perception process occurs. In social psychology, person perception describes the process of how we perceive other people and form impressions to make inferences about their characteristics and personality (Oltmanns & Turkheimer, 2009; von Eckartsberg, 1989). The basic assumption is that when people meet others, they want to know their intentions and goals. As a fundamental part of social life, these impressions of others allow us to rapidly make decisions and predict future behavior (Thornton & Mitchell, 2017). One well-known model that explains the process of how we perceive and categorize others is the stereotype content model, which postulates that we evaluate other people based on two dimensions: their warmth and competence (Fiske et al., 2002). By perceiving the characteristics of a person, for example, which can be similar or dissimilar, humans automatically infer that a person is a member of a certain social group allowing them to predict intentions, feelings, and future actions. According to the stereotype content model, individuals who do not compete for the same resources are considered as warm and individuals with high status as competent. Out-groups, for example, which are considered as warm and competitive can result in envious prejudice, e.g., rich people for a poor person, whereas in-group members with high competence to admiration, e.g., close allies (Fiske et al., 2002). Originally developed to explain social discrimination, the stereotype content model shows the ubiquity of stereotypes during person perception and how our impressions are driven by prior knowledge, expectations, and beliefs.

Transferring this idea to the Proteus effect, the users perceive their avatar and form an impression by assessing it based on its visual appearance and the connected associations and stereotypes, as they (typically) do not have access to any other information about its characteristics, attitudes, and intentions. This higher-level cognitive process is considered a top-down mechanism as the perception is based on beliefs and knowledge gained by prior experiences and acquired stereotypes (Gregory, 1970). Seeing a muscular avatar, for example, may activate stereotypical associations such as physical power, athleticism, attractiveness, or confidence as the users have no other or only limited information they can rely upon to form an impression. Therefore, high-level cognitive structures stored in long-term memory affect the perceptual process (Riener, 2019). This is in contrast to data-driven bottom-up mechanisms where single data detected by our senses flow to the brain and will be then interpreted as an overall percept (Kveraga et al., 2007). This feedforward process is mainly stimulus-based and independent of a perceiver's prior knowledge and expectations (Wolfe et al., 2003). This traditional and simplistic view of perception as a bottom-up phenomenon insulated from the impact of top-down mechanisms is called into question, as it does not represent the actual complexity of perception and how it is affected by contextual information (Freeman & Johnson, 2016; Riener, 2019; Freeman & Ambady, 2011).

Findings from social and cognitive science suggest that both top-down and bottom-up cognitive processes are dynamically integrated during person perception (Freeman & Johnson, 2016; Freeman & Ambady, 2011). As such, Freeman and Ambady (2011) proposed a theoretical framework consisting of a recurrent neuronal network to explain the underlying mechanisms when we encounter other persons (see Figure 2.1). In this highly dynamic and interactive model, the authors argue that we perceive people by iteratively incorporating low-level information, e.g., bodily cues such as hair, the nose shape, or skin color, and high-level factors, e.g., stereotypes, expectations, or goals. This process is repeated as long as a stable state is achieved so that a solid perceptual estimate is created best fitting the bottom-up and top-down input. For example, perceiving a

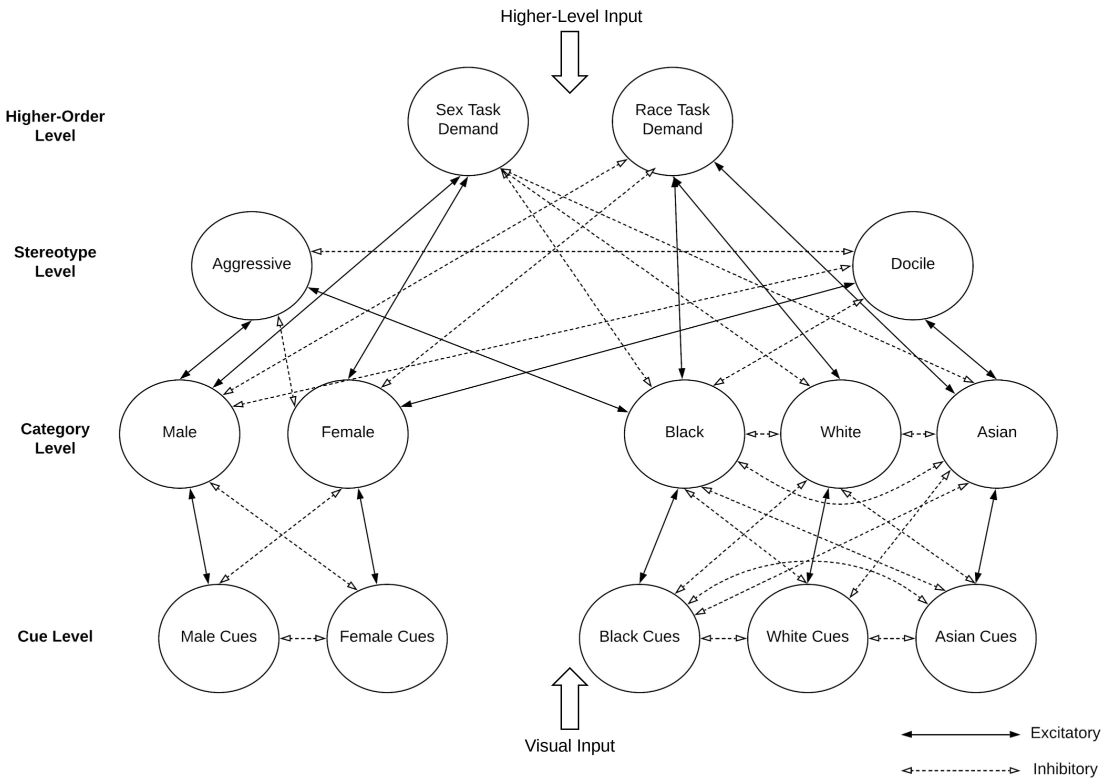

Figure 2.1: A conceptual framework by Freeman and Ambady (2011) modeling the person perception process. This framework uses nodes and their connections simulating the communication between neurons by means of synapses. For example, when perceiving a person the visual input of, e.g., facial characteristics, body posture, etc., activates nodes in the cue level. These nodes activate nodes from higher levels such as the category level, which in turn activate and inhibit nodes from lower levels, e.g., cue level, and higher levels, e.g., stereotypes or other contextual information such as tasks or goals, and so on. This network is interactive so that all nodes interact with each other competing with one another until a stable perceptual estimate is achieved. Eventually, the brain generates a hypothesis best fitting the input and continuously verifies and potentially corrects it using further bottom-up and top-down information. Illustration adapted from Freeman and Ambady (2011).

person causes us to spontaneously and intuitively categorize the person based on certain criteria such as sex or ethnicity (Stolier & Freeman, 2016; Cosmides et al., 2003). Our sensory receptors detect bottom-up characteristics such as "group-typical" features of the face and body allowing us to identify the sex or ethnic group. Additionally, the perceiver's top-down knowledge, e.g., stereotypes, expectations, or goals, biases this perceptual process. During the visual perception of faces, Stolier and Freeman (2016) found that the identification of a category (e.g., male) through facial features (e.g., larger jaw, facial hair) activates associated stereotypes (e.g., aggression) even without displaying any anger, which in turn affect the subsequent assignment to a further category (e.g., dark-skinned). In their study, participants tended to consistently assign male faces as well as dark-skinned faces to angry categorizations, and, therefore, male faces were more frequently perceived as dark-skinned. The authors concluded that top-down and bottom-up processes reciprocally influence each other and that the elicited stereotype of anger and aggression exerted influence on the perception of lower-level information such as skin color or other ethnic-specific features (Stolier & Freeman, 2016).

Particularly when we are exposed to ambiguous stimuli, which cannot be resolved reliably, e.g., male faces with feminine features, top-down influences such as stereotypes play an important role and become dominant during person perception (Freeman & Johnson, 2016; Stolier & Freeman, 2016). This was also demonstrated by Hugenberg and Bodenhausen (2004), who similarly reported that racially ambiguous faces with facial expressions displaying anger were rather perceived as dark-skinned than light-skinned. Hence, we assume that top-down mechanisms are predominant in the Proteus effect due to its high-level and superficial nature, as this phenomenon, by definition, originates from the visual appearance of the avatar and its elicited associations and stereotypes. In a real person perception process, we can typically access multiple sources of information, e.g., facial expressions, tone of voice, body posture as well as behavioral, emotional, and attitudinal cues. Even if it is possible to equip virtual avatars with this combination of verbal and non-verbal abilities through a highly complex character design process, the avatar's visual appearance is usually the primary source the users can rely upon to form an impression during the Proteus effect. Hence, top-down knowledge highly contributes to the perception of an avatar and is used to compensate for the lack of personal information.

2.2.5 Stereotype Threat and Stereotype Lift

Ample research within the field of social psychology has demonstrated that the activation of a stereotype can prime individuals and evoke behavioral and perceptual changes. Steele and Aronson (1995) provided an explanation why these changes occur by introducing the concept of stereotype threat. Stereotype threat describes that people behave in accordance with an activated stereotype, as they are concerned that they might confirm this stereotype. Ironically, it is the fear of conforming to a stereotype that actually makes individuals behave accordingly. Steele (1997), for example, found that the negative stereotype of African Americans or women being bad at math causes individuals who belong to these groups to perform poorly at math tests. The concern that they were judged or treated according to this stereotype resulted in pressure with debilitating and detrimental effects. The mere knowledge about a negative stereotype functions as a psychological "threat" that deteriorates performance. Similar to a self-fulfilling prophecy, Casad and Bryant (2016) stated that "when a stigmatized person becomes aware that their stigmatized status may be relevant in a particular context, they may become vigilant and increase attention for environmental cues relevant to potential prejudice and discrimination". This may then result in feelings of stress, uncertainty, anxiety, and corresponding physiological responses such as increased blood pressure and cortisol level (Casad & Bryant, 2016).

Similar could be shown in the digital world. Ratan and Sah (2015) documented that participants who used female-gendered avatars performed worse on a math task than those who used male-gendered avatars. This is in line with Peck et al. (2020), who induced stereotype threat through female-gendered avatars causing a decreased cognitive performance with regard to the working memory. The authors also found that female participants with male-gendered avatars were not subject to stereotype threat as their cognitive performance remained unaffected. Li et al. (2014) confirmed this theory in a non-immersive exergame. The authors reported that overweight participants who were exposed to stereotype threat through an obese avatar had lower physical activity than when controlling an avatar with a body size the authors dubbed "normal". By controlling the avatar, the users were personally connected with it so that the virtual experience becomes self-relevant causing a "threat in the air" (Steele, 1997), which in turn affected the physical activity.

A further concept that serves as an additional explanation for avatar-induced changes is stereotype lift, which describes the opposite effect in terms of a performance boost due to negatively stereotyped out-groups (Walton & Cohen, 2003). Individuals who are aware of a negative stereotype of a societal group they do not belong to compare themselves with members from this devalued group and, therefore, experience an enhancement in self-efficacy and self-worth (Marx & Stapel, 2006). As opposed to stereotype threat effects, this may alleviate self-doubt, pressure, and anxiety, and in turn, result in an enhanced performance (Walton & Cohen, 2003). Lee et al. (2014) found that participants assigned to male avatars had a better cognitive performance compared to participants with female avatars regardless of their actual gender. In line with stereotype lift, the authors assumed that being represented by male-gendered avatars is motivating and engaging as the negative stereotype of having poor math skills is associated with women and, thus, members of an out-group. Accordingly, Peck et al. (2018) demonstrated that female users embodying male-gendered avatars had an improved cognitive performance due to this gender-swap illusion in VR, as men are not associated with being stereotyped regarding cognitive abilities.

In this case, the lack of stereotypical associations inherently indicates superiority of one group and inferiority of the other group (Clark, 2020), e.g., men are not considered to have superior cognitive abilities but women are thought to have lesser math and science intelligence. Hence, it seems to be sufficient to positively affect the user when a negative stereotype of a competing out-group is prompted. In addition to the embodiment of a male-gendered avatar, Peck et al. (2020) and Peck et al. (2018) therefore actively primed the participants prior to a cognitively demanding task by mentioning that the task produced gender differences. Likewise, Lee et al. (2014) used a competitive scenario with simple and static virtual agents indicating to have the opposite gender compared to the players' avatar to direct the attention towards gender differences.

This is in accordance with Marx and Stapel (2006), who reported that stereotype lift using negatively stereotyped out-group members need to be "pushed" to a greater extent than stereotype threat. Stereotype threat explicitly activates negative stereotypes, e.g., using dark-skinned avatars to foster aggressive behavior in the game as dark-skinned people are perceived more aggressive than white-skinned people (Yang et al., 2014; Hawkins et al., 2021). In contrast, stereotype lift would use non-stereotypes to trigger the opposite effects, e.g., using white-skinned avatars to induce non-violent behavior as white people are not associated with aggressiveness and violence but dark-skinned people are. To induce stereotype lift using avatars, it is, therefore, necessary to use additional cues beyond the avatars' appearance to prime the users to explicitly activate the intended cognitive concepts as a lack of stereotypical associations can also cause the expected behavioral changes to fail to occur. Instead of using avatars that do not belong to a negatively stereotyped out-group, explicit stereotypical characteristics consistent with the intended behavioral changes should be used, e.g., dark-skinned people are more rhythmic than white-skinned people so that users embodying dark-skinned avatars were more active while virtually drumming (Kilteni et al., 2013). This could reduce the variance in behavioral outcomes and the risk of misleading and unintended effects. In this case, stereotypical characteristics would lead to corresponding behavioral influences in the sense of the activated stereotype.

2.2.6 Embodied Cognition

The Proteus effect involves induced body-related changes, e.g., the embodiment of increased cognitive abilities (Banakou et al., 2018). Gibson's Theory of Affordances (Gibson, 1977; Gibson, 1979) postulates that our body serves as a reference frame for perception as objects in our environment are perceived with regard to their affordances or options for action. Accordingly, recent embodied cognition theories emphasize that body representations and body-related information interact with cognitive processes (Dijkerman & Lenggenhager, 2018; Hommel, 2015; Wilson, 2002).

Empirical evidence for these approaches comes from several studies demonstrating that the physical properties and action capabilities of our body influence perceptual estimates regarding the properties of our environment (Harris et al., 2015; Proffitt & Linkenauger, 2013; Witt & Riley, 2014). These studies usually manipulated body-related variables and measured the impact of these manipulations on perceptual estimates about the environment, such as the size or the distance of objects. For example, Linkenauger et al. (2010) induced the illusion of having smaller or larger body parts with magnifying goggles and showed that this rescaling influenced size perception of graspable objects. Another example are full-body illusions of different body sizes that influenced the perception of object size and distance (Weber et al., 2019; van der Hoort et al., 2011). Banakou et al. (2013) showed that adults that embodied a small avatar in a normally scaled VE overestimated the size of objects compared with a baseline condition without embodiment of an avatar. Interestingly, it is not the mere size of the body that influences size or distance perception. Rather, it is the resulting action possibilities that influence judgements about perceptual events in the environment. Having longer arms or generally being larger increases the spatial range of possible actions, which in turn changes our perception of the size or distance of things in the surrounding. An illustration of this aspect is a tool-use study by Witt et al. (2005). Participants estimated the distance of targets that were within and beyond reach. Estimating the distance of these targets and holding a tool that allowed them to reach each target reduced the estimated distance of the targets.

An important aspect regarding the embodiment of avatars is that we perceive our environment not only in terms of the repertoire of possible actions. Perceptual judgments about our environment are also influenced by the assimilated physiological effort required to execute these action possibilities (Proffitt, 2006). Accordingly, objects within reach appear to be farther away when participants have to move their arms against a strong counterforce, compared to a weak counterforce (Kirsch & Kunde, 2013). By manipulating the physical potential of participants, Bhalla and Proffitt (1999) demonstrated that participants estimated hills as steeper when wearing a heavy backpack or when being fatigued after an exhausting run. Similarly, carrying a heavy backpack increased the perceived egocentric distance to a target (Proffitt et al., 2003). Taylor et al. (2011) showed that Parkour athletes that are skilled at climbing walls estimated the height of walls as lower than did novices. This is in line with Tosi et al. (2020), who induced ownership of a body with longer legs. The authors found that participants imagined walking faster when having a body with longer legs compared to a body with standard legs.

Based on these findings from previous work, we assume that the Proteus effect strongly relates to recent embodied cognition theories. Aymerich-Franch (2018) underlined this assumption by explaining that "if an organism of body structure type-A embodies a body with substantially different body properties (i.e., body structure type-B), significant differences should emerge both at the low and high cognitive levels compared to an original organism of body structure type-A". As such, the author highlighted the high dependency of human cognition on the characteristics of the physical body. Similar was explained by Nagel (1974) and then paraphrased by Ratan (2013) that "in order for a human to accurately assume the perspective of a bat, or any other non-human organism, the human would have to take on the physical structures through which the bat experiences life". We, therefore, believe that research investigating embodied cognition approaches can contribute to a deeper knowledge and understanding about behavioral, attitudinal, and perceptual changes caused by the Proteus effect. In addition, VR technology with its ability to temporarily change the users' body representation is a powerful tool to learn about human cognition and, consequently, to advance in this area of research.

2.2.7 Mimicry

Psychologists and neuroscientists have identified a ubiquitous behavioral characteristic of humans known as mimicry. This remarkable phenomenon, which was also observed in animals such as monkeys (Rizzolatti et al., 1999; Gallese et al., 1996) and birds (Prather et al., 2008), describes the mainly unconscious imitation of other's behavior, verbal, and facial expressions as well as emotions during social interaction (Chartrand & van Baaren, 2009). As such, mimicry allows to create rapport, empathy, and liking between the mimickers and the mimickees during interaction, and, therefore, serves as a social function that "binds and bonds" people together (Lakin et al., 2003; Chartrand & van Baaren, 2009). This phenomenon is conceived as "social glue" (Lakin et al., 2003) so that the absence of this natural behavior can negatively influence interaction partners, such as feeling less understood and empathized with others (Stel et al., 2008). In one of the first studies documenting empirical evidence for this phenomenon, Charny (1966) found that the body postures of therapists and their patients have become more similar during the course of the psychotherapy. This behavioral mimicry even positively correlated with the rapport between both of them. In a different context, Yabar et al. (2006) showed that participants mimicked a face touching behavior after observing others rubbing their faces. Another interesting result was presented by Sanchez-Burks et al. (2006), who found that participants performed better at a job interview and had a more positive overall experience when being behaviorally mimicked by the interviewer. Since research from many disciplines has long been interested in this phenomenon, mimicry was observed in a multitude of different behavioral outcomes such as pen playing, food consumption, or smoking (e.g., Chartrand & Lakin, 2013; Chartrand & van Baaren, 2009).

Mimicry is frequently explained by the perception-behavior link (Chartrand & Bargh, 1999; Genschow et al., 2018). Researchers assume that the perception of one's behavior automatically primes the perceiver and thus activates the same behavioral responses (Dijksterhuis & Bargh, 2001; Chartrand & Bargh, 1999). Neuroscientists could also reveal this link on a neurophysiological level by showing that the observation as well as the actual execution of an action activates the same neurons in the brain. As one of the pioneers, Gallese et al. (1996) has investigated these so-called mirror neurons in monkeys. The authors have shown that the mirror neurons fired when the primates observed an experimenter grasping a raisin as well as when they grasped the food themselves. There is also evidence for this physiological mechanism in humans (Kilner et al., 2009; Chong et al., 2008). Chong et al. (2008), for example, found that regardless of whether simple hand gestures, e.g., a finger gun or bouncing a ball, were either observed or executed, the mirror neurons were activated similarly. The observation of other's actions or emotions are simulated through these cells in corresponding brain regions as if we were acting or feeling in the same way. These neural mechanisms allow us to understand other people, and, therefore, play a crucial role in social behavior (Gallese, 2003). Consequently, the discovery of mirror neurons offers a promising physiological explanation for social abilities of humans needed in everyday life, such as feeling empathy for others (Gallese, 2003), observational learning (Petrosini et al., 2003), or (unconsciously) mimicking others (Likowski et al., 2012).

Notably, mirror neurons even fire when activities are merely anticipated instead of actually observed or performed. Previous work documented that a monkey's mirror neurons were activated even if the action was occluded or invisible (Umiltà et al., 2001; Baker et al., 2001). Based on expectations and predictions, mirror neurons predictively discharge before observing or performing the actual activity (Southgate et al., 2009; Maranesi et al., 2014). In this vein, Southgate et al. (2009) reported that the mirror neuron activity had started moments before infants and adults observed someone grasping an object. Similarly, Kilner et al. (2004) concluded that the mere expectation of an upcoming motor movement creates a corresponding mental representation of it and elicits neural responses in one's own motor system. This allows to predict and understand intentions, goals, and further actions before they are actually performed. Such findings can explain how humans predictively mimick others. Genschow et al. (2018) revealed that perceivers frequently touched their noses while watching someone wrinkling the nose. Although this face touching behavior was not directly observed, perceiving others wrinkling their nose caused them to predictively counteract by behaving correspondingly. Consequently, these results from prior investigations indicate not only the reactive but also the anticipatory nature of perceiving and mimicking others.

With regard to the Proteus effect, the knowledge and understanding about mimicry and its underlying processes could contribute to find alternative explanations why the embodiment of avatars make users behave in ways how they are expected to behave. Perceiving an avatar with certain characteristics could trigger stereotypical behavioral associations in the users' mind so that they mentally imagine how persons with such characteristics would behave in a given scenario. This mental representation of, e.g., stereotypical motor movement, can activate the same parts of the brain, which become activated as if the movement was actually performed (Skoyles, 2008). Therefore, the users can access these simulated information allowing them to behave in accordance to the associations and the common expectations connected with the avatars' appearance. For example, the embodiment of animals could then potentially result in behavioral responses such as flapping the arms while embodying a bat (Andreasen et al., 2019) or crawling on all fours while virtually being a tiger (Krekhov et al., 2019a). Such mimicry-related mechanisms seem to be in line with findings from cognitive psychology as well as neuropsychology, however, it is unknown whether the same or similar processes are indeed responsible for this phenomenon. Therefore, a final explanation why the Proteus effect occurs remains unclear so that the precise mechanisms need to be investigated further.

2.3 Determinants of the Proteus Effect

To be able to leverage the Proteus effect in VEs, it is important to know the necessary conditions under which this phenomenon can be induced and which factors can attenuate or amplify it. In a review article about the Proteus effect, Clark (2020) defined basic requirements for this phenomenon to occur. As the Proteus effect originates from an avatar, first of all it is required that the user has to be represented by an avatar in a VE. Second, the avatar needs to have salient and explicit characteristics, which are accessible to the user while controlling or embodying it. Third, these visual characteristics have to be associated with a popularly-held stereotype, which in turn has to be accessible while controlling or embodying the avatar. Fourth, a certain behavior or attitude has to be associated with the stereotype and, finally, there must be an opportunity for the user to perform the behavior and act in a stereotype-congruent way, i.e., when a stereotype for superior intelligence is evoked, the user should be able to perform a cognitive task. Interestingly, the authors argue that if one of these requirements is absent then the induced behavioral changes should not be attributed to the Proteus effect but to different paradigms, e.g., perspective taking or the "Doppelganger effect".

2.3.1 Perspective Taking

During perspective taking, a person should mentally imagine being someone else, e.g., a member of a different societal group (Fiske, 2015), and experience a situation from this adopted “new” perspective. VR supports this mental imagery process by allowing the user to experience the VE from a first-person perspective and vividly visualizing what it would be like to embody someone else. Peck et al. (2013), for example, found that light-skinned users had a lower racial bias when embodying dark-skinned avatars. These findings are in line with perspective-taking mechanisms, which increase the users’ empathy and compassion for people that are different from them (van Loon et al., 2018). In a TED talk[1], the filmmaker Chris Milk accordingly denoted VR as the “ultimate empathy machine” (Milk, 2015), as it allows users to experience virtually anything from another person’s point of view (Herrera et al., 2018; Bevan et al., 2019). Herrera et al. (2018), for example, found that participants felt empathetic and connected to homeless when they experienced what it was like to become homeless in VR. As one of the rare studies focusing on long-term effects, the authors also showed that these attitudinal effects even lasted over eight weeks.

Empathy-promoting effects caused through virtual perspective taking could be demonstrated in a variety of behavioral and attitudinal outcomes. Hasler et al. (2017) reported an increased mimicry between light-skinned participants who embodied dark-skinned avatars and dark-skinned agents. Researchers also documented that participants were more emotionally connected to the depicted events when experiencing the military prison located at Guantanamo Bay through a prisoner’s point of view (de la Peña et al., 2010). More recently, however, Banakou et al. (2021) revealed that the effects on users caused by the embodiment of avatars depend on the social setting. The authors showed that light-skinned participants’ racial bias while being embodied in a dark-skinned avatar even increased when the surrounding crowd of virtual NPCs behaved negatively, e.g., turning away from them or frowning while looking at them. These findings are in line with Neyret et al. (2020), who exposed participants to a virtual scenario of sexual harassment of a lone woman by a group of men in VR. Participants either experienced this scenario from the woman’s or the men’s point of view. One week after the virtual exposition, a Milgram’s obedience experiment (Milgram, 1963) was performed in VR. Instead of an increased empathy for the female character, participants who previously embodied an avatar being part of the harassing male group gave more electrical shocks to the virtual female agent compared to other conditions. These findings imply that a

[1]TED stands for Technology, Entertainment, Design and is a non-profit organization arranging international conferences and talks that cover a variety of timely topics from science to business as well as global issues, `https://www.ted.com/`

relationship of avatar embodiment and positive or beneficial behavioral and attitudinal outcomes cannot be assumed per se. Due to these controversial results, adverse effects have to be taken into account when designing embodied experiences in VR. Hence, it seems that whether VR can be an "ultimate empathy machine" highly depends on the situation and events in VR.

According to Clark (2020), there is a conceptual difference between the Proteus effect and virtual perspective taking, as the latter attempts to affect personally-held beliefs (i.e., in-here stereotypes) instead of using stereotypical beliefs that are shared and present within a wider population (i.e., out-there stereotypes). From an HCI perspective, this has to be considered as individual beliefs can obviously be different from others' beliefs. When using the Proteus effect, designers and researchers have to anticipate the users' stereotypical assessments to be able to predict the expected behavior in VR. Due to the possible discrepancy between what users think and what they belief others think when perceiving an avatar, it is difficult to know what attributes should be used to activate the intended stereotype. When using an "elderly" avatar, for example, to prime relaxation and leisureliness, users may perceive the avatar differently than predicted when a near relative elderly is very active and athletic.

In this case, the in-here stereotype would be predominant and, therefore, the contrary cognitive concepts would be activated. To reduce the variance in behavioral responses, the characteristics of the target population as well as the applied stereotypes have to be well-known. From a research perspective, however, it is hardly feasible to completely isolate these two classes of stereotypical beliefs from each other without compounding different effects. To gain understanding about the Proteus effect, HCI research attempts to isolate this phenomenon from other effects by mainly using the avatars' visual appearance to activate certain associations. Even if it is conceivable to use additional information to ensure the activation of out-there stereotypes, e.g., prompting the users not to focus on what they think but rather on what they belief others think, this would already prime the users and in turn confound the causal relationship between the mere avatars' characteristics and the users' behavioral changes. Hence, researchers and designers should be aware of the stereotypes and characteristics of a target population to be able to induce the desired effects via the avatars' appearance.

2.3.2 User Identification and Anonymity

In contrast to the Proteus effect, the “Doppelganger effect” describes behavioral changes caused by a virtual character with visual characteristics strongly resembling the user. Ahn et al. (2014), for example, showed that virtual doppelgangers were more effective in increasing the awareness and perception of risks of an unhealthy diet, e.g., sugar-sweetened beverages, than unfamiliar virtual humans. However, such effects cannot be attributed to the Proteus effect, as the virtual doppelganger was neither embodied nor controlled but only observed from a third-person perspective. Nevertheless, these findings are important for research on the Proteus effect, as they suggest that self-similarity and identification with the avatar enhance the users’ personal connection to the virtual experience. Prior work revealed that the identification with avatars can moderate the Proteus effect, as it can lead to a higher personal relevance of the avatar (Praetorius & Görlich, 2020). Birk et al. (2016) showed that avatar customization could make users put more effort into playing a game. Similarly, Turkay and Kinzer (2014) found that users who customized their avatars could better identify with the avatar and were personally more connected to the virtual experience. While the BOI describes the feeling of owning and inhabiting a virtual body, user identification is a cognitive and emotional state where users are not aware of themselves and refer to their virtual identity in the VE as “I” (Looy et al., 2012). Users, therefore, “turn” into the avatar and experience virtual events from inside as if they were actually happening to them (Cohen, 2001; Klimmt et al., 2009).

Researchers agree that the higher the identification with the avatar, the stronger the bond between avatar and user potentially resulting in an augmented Proteus effect (Praetorius & Görlich, 2020). This is in accordance to Ratan et al. (2019), who argued that the Proteus effect is enhanced when users can connect self-related and avatar-related cognitive schema. This implies that users can experience a sense of identification with the avatar. Putting it simply, when the users’ self-related concepts and beliefs, e.g., “I am fit and athletic”, fit the concepts that are associated with the avatar, e.g., “the avatar is athletic and strong” in terms of a muscular avatar, the higher the probability that the intended behavioral outcomes occur, e.g., higher physical activity in an exergame (Peña et al., 2016). We also argue that the opposite self-related concepts, e.g., “I am not fit and non-athletic”, would result in similar (or maybe even larger) effects due to motivational factors, as the mere presence of concepts regardless of whether they are positive or negative, e.g., perceiving oneself as athletic or non-athletic, allows the user to identify with the avatar. This notion is supported by Looy et al. (2012), who proposed that, besides self-similarity and the sense of presence, “wishful identification”—the desire of the user to be more like the avatar—is an important factor contributing to the user identification. The desirable traits of an avatar can reduce self-discrepancy by allowing users to identify with this character and feel better about themselves. For example, users that perceive themselves as less athletic than they actually want to be can temporarily experience how it feels to embody athleticism in terms of an athletic avatar. Interestingly, Koulouris et al. (2020) found that idealized characteristics of an avatar that users perceive as unachievable can reinforce the discrepancy between users’ and avatars’ perceived physical abilities. As a consequence, this can be demotivating and can result in adverse effects.

The authors found that idealized avatars decreased physical performance on an ergometer bike, however, avatars with realistically enhanced characteristics had a positive impact on the users. As such, previous work found that undesirable characteristics, e.g., narcissism triggered by the embodiment of Kim Kardashian (McCain et al., 2018), could be a barrier to the Proteus effect. Users tend to refuse to behave in line with the perceived traits and, therefore, behaviorally counteract to compensate them. Accordingly, research showed that the users’ personality can affect the extent of the Proteus effect, e.g., their shyness level (Bian et al., 2015), the locus of control (Dewez et al., 2019), or how strongly they belief in the activated stereotype (Sherrick et al., 2014). Consequently, from an HCI perspective it is important to use avatars that represent desirable attributes, which should not be perceived as too unrealistic and unachievable by users as this may deteriorate the identification with the avatar and the extent of the Proteus effect.

When users are represented by an avatar, the avatar is their temporary “new” identity. This can elicit a sense of anonymity as their real self is replaced by the avatar in the VE. Therefore, the avatar serves as a mask the user is wearing so that other users sharing the same VE only perceive the virtual representation during interaction (Adams, 2010). In online games, for example, users frequently do not even know the real person hiding behind the avatars (Turkay & Kinzer, 2014). According to the social identity model of deindividuation effects (Reicher et al., 1995), this anonymity contributes to deindividuation. This, in turn, makes users amenable to the identity cues prompted by the avatar and, eventually, reinforces behavioral conformity. This model actually emphasizes collaborative settings and how an individual suppresses personal identity in favor of the social identity of a group to adhere to the group norms. As it is still unclear how the context of a virtual scenario affects the Proteus effect (Van Der Heide et al., 2012), e.g., being alone as opposed to being together with others in a VE, this model may be used to explain or predict possible effects.

2.3.3 Body Ownership of Avatars

As already mentioned in the previous sections, the experienced body ownership of the avatar is a crucial moderator of the Proteus effect. Osimo et al. (2015) found that avatars have a stronger cognitive impact on the user when moving synchronously with them than avatars reacting asynchronously to the user's motion. When users embodied Sigmund Freud—a representation of high competency in psychotherapy and psychology—while providing counseling to themselves, their mood improved to a greater extent when the Freud avatar mimicked them instead of moving autonomously using predefined animations. Similar was shown by Banakou et al. (2013), who found that visuo-motor asynchrony even extinguished avatars' effects. As the spatiotemporal synchronicity of multimodal stimulation is known to modulate the BOI, the authors argue that the experienced body ownership of an avatar determines to what extent users attribute the avatars' characteristics to themselves. Consequently, they showed that users only overestimated the size of virtual objects when a child avatar's movements were in synchrony with the users' ones.

Other findings indicating that the Proteus effect depends on the body ownership were presented by Ash (2016), who found that users behaved more aggressively during a boxing game when they experienced a higher embodiment of dark-skinned avatars. Although all these studies provide empirical evidence for the relationship between body ownership, user identification, and the Proteus effect, more research is required to gain a deeper understanding of the interplay of these concepts. Particularly factors, which are known to be significant moderators of BOIs should be further analyzed within the context of the Proteus effect, e.g., the embodiment time (Tsakiris & Haggard, 2005; Keenaghan et al., 2020; Oyanagi et al., 2021), the camera perspective (Slater et al., 2010), or the sense of immersion (Stavropoulos et al., 2021). Nonetheless, these findings imply that it is important to understand how to design and create appropriate avatars to be able to activate the intended associations without deteriorating concepts such as body ownership and user identification, which significantly contribute to the Proteus effect.

2.4 The Proteus Effect in Virtual Reality

Due to the rapid advance in immersive technologies, VR has been frequently applied to induce the Proteus effect using full-body avatars. This phenomenon can also occur in non-immersive environments, e.g., video games such as *World of Warcraft* (Blizzard Entertainment, 2004; Yee et al., 2011) and *Wii Fit* (Nintendo EAD, 2007; Peña & Kim, 2014; Peña et al., 2016), or online virtual worlds such as *Second Life* (Linden Lab, 2003; Buisine et al., 2016) and *The Sims* (Maxis, 2000; Bian et al., 2015). However, it seems plausible to assume that the Proteus effect is augmented in VR due to its ability to produce immersive and vivid experiences, e.g., through a high level of body ownership of an avatar or sense of (embodied) presence in a VE. There are three literature reviews about the Proteus effect (e.g., Praetorius & Görlich, 2020; Ratan et al., 2019; Clark, 2020), which showed that this phenomenon has been evidenced in a broad variety of contexts and domains in immersive virtual worlds, e.g., financial risk behavior (Hershfield et al., 2011), consumer preferences (Ahn & Bailenson, 2011), or sexual thoughts (Fox et al., 2013).

Prior work about the Proteus effect frequently investigated this phenomenon after the virtual experience. Banakou et al. (2018) showed that participants performed better at a cognitively demanding task after embodying Albert Einstein. Similarly, Yee and Bailenson (2007) found that the embodiment of a taller avatar influenced the subsequent negotiation behavior outside of VR. Another series of studies showed a decreased racial bias after embodying light-skinned participants in dark-skinned avatars (Banakou et al., 2016; Peck et al., 2013; Salmanowitz, 2018; Groom et al., 2009). Reinhard et al. (2020) also showed that walking speed could be affected as a consequence of embodying older-looking avatars. After leaving VR, participants walked significantly slower when they previously embodied an elderly avatar compared to a young-looking avatar. As the walking speed was not affected for the entire walking distance but only for the first half, it seems that the Proteus effect tended to decrease rapidly over time. Therefore, the authors assumed fast decay rates (Reinhard et al., 2020). However, the temporal stability of the Proteus effect and its impact on users from a long-term perspective is still underexplored. Overall, these results suggest that behavioral and attitudinal changes caused by the Proteus effect can even retain after the VR experience for an undefined amount of time. When considering VR as a technology applied for health and sports interventions, e.g., for therapeutic purposes to treat mental health problems (Rizzo & Koenig, 2017) or fitness applications for promoting physical activity (Costa et al., 2019), the Proteus effect may be a promising method to build more effective "serious" applications for purposes other than pure entertainment.

From an HCI perspective, this phenomenon could also be used to improve the user performance within VEs. Peck et al. (2020), for example, could increase the female participants' working memory through a virtual gender-swap illusion by embodying them in male-gendered avatars. By doing so, the authors prevented stereotype threat effects to occur, as the male avatar eliminated the "threat" of women performing poorly at cognitive tasks. In a first-person VR game, Christou and Michael (2014) found that players who embodied an avatar wearing a robust and powerful-looking suit performed better at blocking incoming cannon projectiles compared to an avatar with casual clothes without a protective suit. Navarro et al. (2020) documented that participants who were watching an avatar dressed in sportswear textured with the participant's face tended to be more physically active while running compared to avatars with formal clothes representing a stranger's face. These findings are in line with previous work showing that avatar-user similarity can increase the user identification (Peña et al., 2021) and body ownership (Jo et al., 2017), which can, in turn, result in an amplified Proteus effect (Praetorius & Görlich, 2020).

2.5 Summary

This chapter presented the background and previous work on BOIs and the Proteus effect. Following the structure of this thesis, an overview of BOIs in real-world settings and in VR was provided to learn about the cognitive mechanisms underlying this phenomenon. Our knowledge about BOIs is primarily based on empirical findings from real-world experiments such as the RHI, which has evolved into a key instrument for investigating BOIs. Researchers and designers of VR applications, therefore, apply the knowledge gained from RHI experiments to induce a sense of body ownership of avatars and create embodied experiences. Interestingly, there is no empirical evidence that the principles that govern the induction of the RHI are the same as in VR. An understanding thereof is important to inform the design of avatars and the ways of induction of BOIs in virtual worlds. We, therefore, compared a RHI in the real world and a RHI in VR to obtain first insights into the differences and similarities between the embodiment of physical and virtual entities (RQ1). In addition, we reviewed research on avatars that strongly deviate

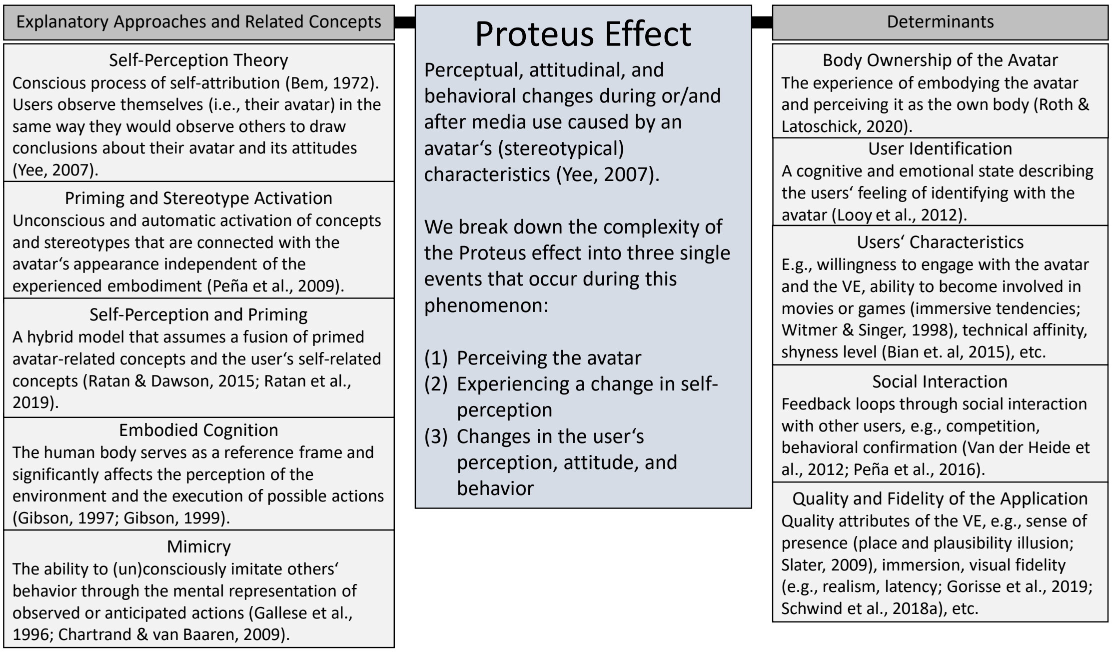

Figure 2.2: Overview and summary of theoretical explanations and determinants of the Proteus effect. Illustration inspired by Praetorius and Görlich (2020).

from the users' physical body. Even if the term "homuncular flexibility" was coined to describe the users' ability to adapt to avatars with altered body structures, the limits of acceptable violations still remain unclear. From an HCI perspective, an increased understanding of the effects of avatars with features that deviate from the users' actual body or even from the human norm is important not to negatively affect the behavior and VR experience. As hands and fingers are one of the most important body parts for interaction using avatars, we address this by manipulating the realism of virtual hands and systematically removing individual fingers (RQ2).

The second part of this chapter focused on the Proteus effect and theoretical approaches explaining this phenomenon. Figure 2.2 shows an overview of all terms and theories addressed in this chapter. Previous work demonstrated behavioral, attitudinal, and perceptual changes caused by an avatar's appearance in a variety of different contexts (Ratan et al., 2019). The question remains whether the Proteus effect can be harnessed in a systematic and targeted way to improve performance in VR and create enhanced VR experiences. It is currently unknown whether avatars with attributes that are associated with high physical abilities can indeed motivate the users and make them perform better than they would in casual embodiments. As one of the most important human behavioral characteristics is exerting force, we explored whether muscular (RQ3) and athletic (RQ4) avatars can improve physical performance in VR. As theories from social psychology postulate that other people affect one's own behavior (e.g., behavioral confirmation), we also explored the Proteus effect in the context of multi-user environments. Research found that embodying Einstein as a stereotype for superior intelligence can increase cognitive performance. However, it remains unclear how such effects are moderated by social interaction and whether they can also occur in a CVE. We addressed this with RQ5.

3

Understanding Body Ownership in Virtual Reality

To utilize the Proteus effect in VR, it is important to understand how to create the sensation of owning a virtual avatar. As we learned in the previous chapter that the body ownership of avatars is a crucial determinant of the Proteus effect, it is necessary to gain a deeper understanding of BOIs in VR. In this chapter, we, therefore, aim to learn about the underlying mechanisms of BOIs and understand how to elicit a sensation of owning a virtual avatar. One way to learn about body ownership is the seminal RHI paradigm that has evolved into a well-established instrument for understanding human cognition and the integration of foreign bodies and limbs into the own body schema. Hence, we conducted a RHI experiment in the real world and in VR to make users experience an artificial hand as their own one. We successfully induced an ownership illusion of a physical and virtual rubber hand using visuo-tactile synchrony by simultaneously stroking the rubber hand and the participants' real hand. We also found that the RHI can affect the skin temperature of the own hand. The results contribute to our understanding of how to induce a sense of ownership of virtual avatars in VR and provide interesting insights into the consequences for the real body. This chapter presents an experimental setting to systematically induce the RHI in reality and in VR and discusses the findings in the context of virtual avatars.

This chapter is based on the following manuscript (currently unpublished):

Kocur, M., Kalus, A., Bogon, J., Henze, N., Wolff, C., & Schwind, V. (n.d.). "The Rubber Hand Illusion in Virtual Reality and the Real World - Comparable but Different." In: *Currently under review*.

3.1 Background and Research Rationale

Designers aim at establishing a feeling of embodiment of avatars to make users feel represented and experience control over the actions executed in the VE (Seinfeld et al., 2021). For this reason, understanding BOIs and the underlying mechanisms is important for the design of avatars and immersive VR experiences in general, and the Proteus effect in particular. Our knowledge about body ownership is mainly based on experiments in the real world such as the seminal RHI, which has evolved into a key instrument for investigating the embodiment of artificial limbs and significantly contributed to a better understanding of human cognition and bodily awareness (Riemer et al., 2019).

The importance of the RHI is not limited to the understanding of human perception. Understanding the RHI has implications for the design of immersive VEs in general and avatar creation in particular. Consequently, the knowledge from RHI experiments in the real world is transferred into VR to make users experience ownership of virtual avatars (Seinfeld et al., 2021). For years, designers and researchers have adopted the principles that govern the induction of the RHI to induce BOIs in VR. Previous work found, for example, that users feel ownership of virtual hands when they see the virtual hands from a first-person perspective while both the virtual and real limbs are synchronously stroked (Slater et al., 2008). Although it is known that users can even feel ownership of full-body avatars in VR, there is currently no empirical evidence that the mechanisms that apply in the real world are the same as in virtual worlds. This is particularly important for simulation technologies such as VR, which aims at precisely reproducing the real world. Understanding the degree of concordance between the VE and the corresponding real world is, therefore, crucial for creating immersive and embodied VR experiences. Research from psychology, for example, extensively compares the effects of in-vivo and VR interventions to determine if they cause similar treatment outcomes (Carl et al., 2019). However, there is a lack of systematic comparisons between BOIs in the real world with BOIs in VEs. Hence, it is unclear whether there is a difference between the effects caused by the embodiment of a physical entity in the real world, e.g., a physical rubber hand, and the embodiment of virtual avatars in VR, e.g., a virtual hand (Schwind et al., 2018a). A comparison between BOIs in both environments would validate that the principles that apply for BOIs in the real world translate to VR. Hence, we could find out whether VR requires methodological adaptations to induce ownership of virtual avatars (e.g., longer stimulation periods through visuo-tactile synchrony in VR compared to the real world). The RHI is a promising paradigm for this to explore as it allows to induce an ownership illusion of a physical rubber hand in the real world and it can be transferred into VR to create the illusory sensation of embodying a virtual rubber hand.

To learn about the fundamentals of BOIs and how we can elicit the sensation of owning an artificial limb, we induced the RHI in the real world and compare it with a RHI in VR. We also explored physiological responses to the embodiment of a rubber hand in terms of skin temperature changes of the own hand. We found systematic effects of the RHI conducted in the real world and in VR on the proprioceptive drift and the questionnaire ratings indicating that we successfully induced the RHI in both environments. Our results also revealed effects on the skin temperature of the own hand. We discuss our findings in the light of theories on psychological "disownership" of real body parts and provide implications for the virtual embodiment of avatars in VR. In this chapter, we also contribute with an experimental setting to systematically induce the RHI in reality and in VR, and increase our understanding of embodying virtual limbs.

3.2 Method

To learn about BOIs and the induction methods, we induced a RHI in the real world and in VR based on the experimental procedure by Moseley et al. (2008). To compare the magnitude of effects between both environments, we conducted a RHI experiment in VR using the same experimental procedure as in the real-world setting. We further explored whether the RHI can cause skin temperature changes of the own hand.

3.2.1 Study Design

We conducted a study using a within-subjects design with two independent variables. To determine whether the effects of the RHI induced in the real world differ from a RHI

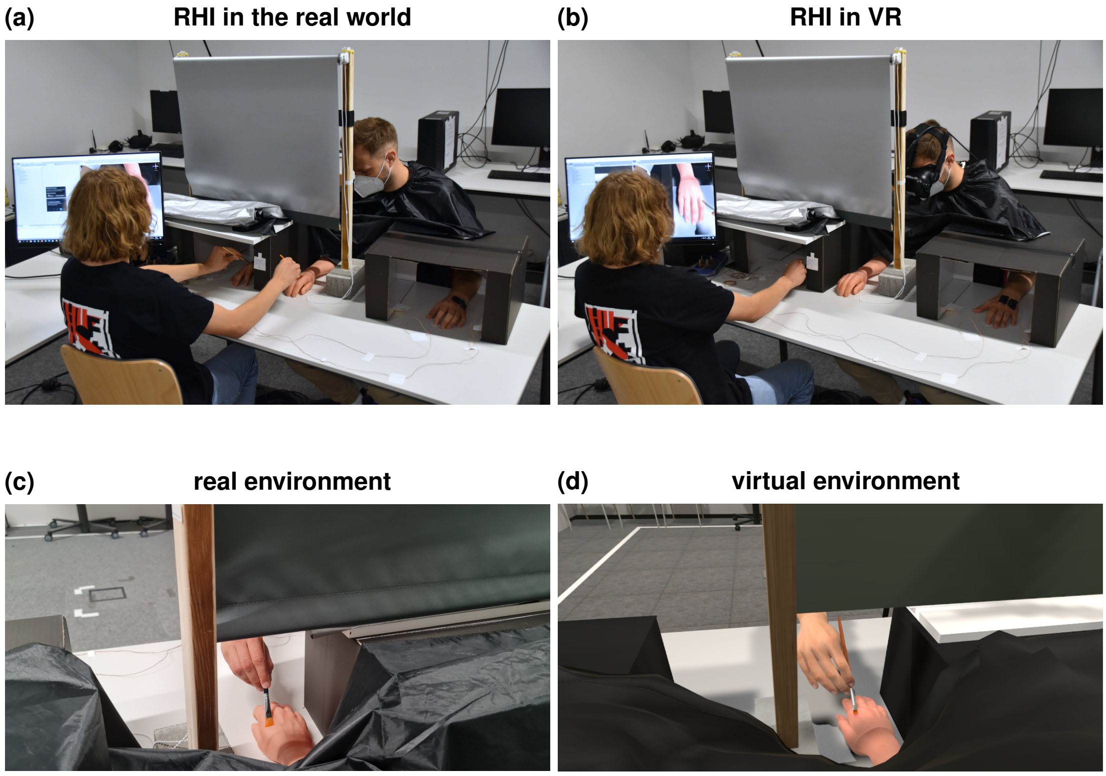

Figure 3.1: RHI performed in the real world (a) and in VR (b), and the participants' view of the real environment (c) and the VE (d).

induced in VR, we used the independent variable ENVIRONMENT with the two levels *real* and *VR*. In the *real* condition, the RHI was conducted in the real world whereas in the *VR* condition, the RHI was conducted in VR using a virtual replica of the real environment (see Figure 3.1). As previous work found that it is crucial that the real hand and the rubber hand are touched at the same time to induce the RHI, and that temporal deviations between the seen and the felt touch stop the illusion from occurring (Kilteni et al., 2015), we systematically manipulated the synchrony of the applied tactile and visual cues to modulate the RHI. Hence, we used the independent variable SYNCHRONY with the two levels *synchronous* and *asynchronous*. In the *synchronous* condition, we synchronously stroked the participants' real hand and the rubber hand in time and at the correct position so that the participants saw and felt the stroking congruently. In the *asynchronous* condition, we created a temporal delay of approximately 5 seconds (duration of one stroke) between the stroking on the rubber hand and the real hand by stroking both of them alternately. The real hand was stroked immediately after stroking the rubber hand. This temporal delay between the visual perception and the tactile perception of the stroking should prevent the illusion from occurring (Botvinick & Cohen, 1998; Erro et al., 2018). Hence, the asynchronous stimulation served as a control condition allowing to control for effects caused by the embodiment of the rubber hand. Consequently, our experiment was carried out using four conditions: 2(*real* and *VR*) $\times$ 2(*synchronous* and *asynchronous*). To reduce order effects, we counterbalanced the order of the conditions employing all possible permutations.

3.2.2 Measures

We took multiple measures to determine the effects of the independent variables. We assessed the proprioceptive drift and used a RHI questionnaire (Longo et al., 2008) for quantifying the RHI. Additionally, we measured the skin temperature of both hands during the entire course of each condition to analyze how the skin temperature evolves across time. As handedness does not modulate the extent of the RHI (Smit et al., 2017), we determined the right hand to be the stimulated hand, which was stroked and hidden from view during the procedure. The left hand was used as a control hand (unstimulated hand) and was neither touched nor seen during the RHI procedure.

3.2.2.1 Proprioceptive Drift

We measured the proprioceptive drift, which describes a shift of the stimulated hand's perceived location towards the rubber hand. Botvinick and Cohen (1998) found that participants mislocated the perceived position of their stimulated hand during the RHI, and estimated their hand to be closer to the rubber hand. Consequently, a higher proprioceptive drift indicates a stronger RHI (Tsakiris & Haggard, 2005). To assess this illusory drift, we used the ruler technique, which is a widely used strategy to quantify the proprioceptive drift (Riemer et al., 2019). After each condition, we placed a ruler above the participants' right hand (stimulated) and the rubber hand, which were both hidden and could not be seen during the assessment of the proprioceptive drift. We then asked the participants to verbally indicate the number that is directly above their own index finger.

3.2.2.2 RHI Questionnaire

We asked the participants to fill the RHI questionnaire designed by Longo et al. (2008) for quantifying the experienced RHI. The questionnaire consists of seven-point Likert items ranging from "strongly disagree" to "strongly agree". The items reflect five dimensions: *embodiment of the rubber hand*, *loss of own hand*, *movement*, *affect*, and *deafference*. The dimension *embodiment of rubber hand* related to the experience that the rubber hand belonged to the participants and was accepted as the own one. The dimension *loss of own hand* represents the experience that the own hand is disappearing and that the control over the own hand is lost. The dimension *movement* referred to the perceived motion of the real hand as well as the rubber hand. This dimension was related to the proprioceptive drift and consisted of items such as "it seemed like my hand was moving towards the rubber hand" or "it seemed like my rubber hand was moving towards my hand". The dimension *affect* related to the experience being interesting and enjoyable. The fifth dimension was termed *deafference*, which related to the feeling of pins-and-needles and numbness in one's own hand, and the experience that the own hand is less vivid than normal (Longo et al., 2008). For the *VR* condition, we changed the term "rubber hand" into "virtual rubber hand". At the end of the questionnaire, we added an additional item that should explore whether the participants perceived any change in skin temperature in the right hand (stimulated). Accordingly, we used a seven-point Likert item ranging from "cooling" to "heating". In all conditions, the questionnaire was administered on a desktop computer.

3.2.2.3 Skin Temperature

We continuously measured the participants' skin temperature on their right and left hand to control whether potential effects on skin temperature are limb-specific. If effects on the skin temperature originate from the embodiment of the rubber hand, they should not occur on the unstimulated hand (Moseley et al., 2008). We, therefore, evaluated the time course of the temperature difference between the right hand (stimulated) and the left hand (unstimulated) across the entire stroking procedure. To calculate the temperature difference between both hands, we subtracted the temperature on the left hand (unstimulated) from the temperature on the right hand (stimulated): $\Delta t = t(\mathit{stimulated\ hand}) - t(\mathit{unstimulated\ hand})$. A negative difference indicates a lower temperature in the right hand (stimulated) than in the left hand (unstimulated). We, therefore, hypothesize that the negative difference between both hands increases over time due to a decrease in temperature of the right hand (stimulated). Additionally, we also analyzed the absolute skin temperature of the right hand (stimulated) and the left hand (unstimulated) across time.

3.2.3 Apparatus

We used two black cardboard boxes (dimensions: 45 cm $\times$ 35 cm $\times$ 23 cm) with cut holes placed on a table in front of the participants to hide their hands (both the right and the left hand) during the RHI. The male experimenter sat opposite the participants and used two common paintbrushes to stroke the rubber hand and the participants' right hand. The experimenter also used in-ear headphones and a metronome application running on a smartphone for pacing each stroke. As prior investigations found that seeing the experimenter during the stroking may influence the experience of touch (de Haan et al., 2017; Fusaro et al., 2021), we used a window roller blind mounted on two wooden bars to avoid that the participants could see the experimenter during the RHI. Thus, the participants only saw the experimenter's hand stroking the rubber hand. A life-sized rubber model of a right human arm (AFM-BLM Male flexible arms large hands medium arms, Hollands Wondere Wereld vof, Oostwoud, the Netherlands) was placed in front of the participants in an anatomically plausible posture. The participants wore a large black hairdressing cape to cover the forearm of the rubber model and to ensure that the participants could not see their own body parts during the RHI. Hence, we created the visual impression that the rubber hand was the participants' own outstretched hand placed on the table.

To measure the participants' skin temperature, we used a professional thermometer module with a sampling rate of 10 Hz and a resolution of 20 bit (TC-08 8-Channel USB Thermocouple Data Acquisition Module, Omega Engineering, Norwalk, USA). We used four insulated T-thermocouples (Fast response insulated thermocouple with connectors: 5SRTC-TT-TI-20-2M, Omega Engineering, Norwalk, USA) to assess the skin temperature on each hand. To increase measurement accuracy and compensate for a potential malfunction of a thermocouple, we attached two thermocouples on the back of the right hand and another two on the back of the left hand using a common adhesive tape. To assess the proprioceptive drift, we used a printed paper ruler (centimeter ruler for A3 paper, 80 cm) placed on a wooden board. As the proprioceptive drift was measured four times in total (once per condition), we used four rulers with different scales to avoid biased answers caused by the recall of previous responses and memory effects. Each ruler was only used once per experiment and was randomly chosen for the conditions. Additionally, the experimenter used a USB footswitch to log UNIX timestamps for determining the start and end of each condition.

To be able to compare the RHI conducted in the real world and the RHI in VR, we designed a virtual replica of the real environment with the identical experimental setup as in reality (see Figure 3.1). We used the game engine Unity3D (v. 2019.2.1f1) to develop the VR application. We designed a virtual rubber hand using a rubber shader. We also designed a realistic virtual hand holding a paintbrush, which represented the experimenter's hand stroking the virtual rubber hand. To avoid tracking errors and reduce temporal deviations between the applied tactile and visual cues due to the latency of the VR system, we created a stroking animation to precisely simulate the stroking of the experimenter. A screen was placed next to the experimenter displaying the participants' view of the VE. This allowed the experimenter to align the stroking of the real hand to the stroking of the virtual hand in the *VR* condition.

We used an HTC Vive HMD (HTC Corporation, Tayuan, Taiwan) with a wide horizontal field of view of 100° and a spatial resolution of $1080 \times 1{,}200$ pixels per eye. The target frame rate of the applications was 90 frames per second (FPS) while antialiasing and global illumination were enabled. The participants perceived the VE from a first-person perspective. In line with the real environment, their virtual body was covered by a cloth-simulated cape. The VR application ran on a desktop PC (Windows 10, Intel i7-8750H, 16GB RAM, NVIDIA GeForce GTX 1060 graphics card).

3.2.4 Participants

We recruited 24 participants (14 male, and 10 female) through our university's mailing list and public forums. Their age ranged from 19 to 29 years ($M = 23.91$, $SD = 2.45$). All of them had either normal or corrected-to-normal vision. None of them reported any pain in the upper limbs (shoulder, arm, or hand region) before the study. One participant was left-handed. Participants received course credits for participating in the study. They were informed that they could withdraw or discontinue the experiment at any time without penalty.

3.2.5 Procedure

Throughout the study, we followed the current hygienic measures according to the regulations of the government and our institution. After welcoming the participants, we explained the procedure of the study. We then asked them to sign an informed consent form and to complete the demographics questionnaire. Afterward, the participants sat at the table at a predefined position 37.5 cm from the body's midline (coronal plane) to the rubber hand. In the *VR* condition, the experimenter helped the participants with putting on the HMD, adjusted it to their head, and calibrated the interpupillary distance if necessary. Afterward, the participants put their right and left hand into the cardboard boxes to keep both hands out of view. The experimenter placed the hairdressing cape over the participants' shoulders to cover their body and the forearm of the rubber hand model. The experimenter then took a seat opposite the participants and attached the thermocouples on both of their hands using tape. The experimenter precisely positioned the participants' hands at a fixed location marked with tape strips on the table. The participants were asked to keep their hands still during the procedure. The tip of the right index finger was 22.5 cm from the rubber hand's tip of the index finger. This distance conforms to the mean of distances used in a series of studies by Moseley et al. (2008). Before a trial started, the roller blind was lowered to ensure that the participants could not see the experimenter except for the hand stroking the rubber hand.

The experimenter started the conditions by pressing the footswitch and beginning to stroke. Each stroke started from the wrist along the index finger to the fingertip resulting in a stroking distance of ~15 cm. In line with current recommendations about stroking velocity (Riemer et al., 2019), we used a velocity of ~3 cm/s so that each stroke lasted ~5 s. After a stroke, the experimenter immediately repositioned the brushes at the wrist and started the next stroke. In the *VR* condition, a stroking animation was displayed so that the experimenter only stroked the real hand aligned to the animation. After three minutes of stroking per condition, the proprioceptive drift was assessed. Therefore, the roller blind was rolled up and the ruler attached to a wooden board was placed above the participants' right hand as well as the rubber hand. We asked the participants to verbally indicate the number that is directly above their own index finger. In the *VR* condition, the experimenter triggered an event using the HTC Vive controller, which simulated the real-world setting by automatically rolling up the virtual roller blind and placing the virtual ruler at the same position in the VE.

The experimenter then removed the thermocouples and helped the participants with taking off the hairdressing cape and the HMD. Afterward, the participants completed the RHI questionnaire on a desktop computer. This procedure is repeated for each condition. At the end of the study, the participants were asked to give general feedback about the experience and the RHI in the real world as well as in VR. The study took 60 minutes per participant in total.

3.3 Results

Our measures consist of parametric data. We used Shapiro-Wilk tests to determine the assumption of normal distribution of the proprioceptive drift and the scores of the RHI questionnaire. As the skin temperature is a ratio-scaled measurement, we assume a normal distribution of the skin temperature data.

3.3.1 Proprioceptive Drift

A 2(ENVIRONMENT: *real* vs. *VR*) $\times$ 2(SYNCHRONY: *synchronous* vs. *asynchronous*) analysis of variance (ANOVA) with repeated measures on both factors on the proprioceptive drift revealed a significant main effect of ENVIRONMENT, $F(1,23) = 14.426$, $p < .001$, $\eta_p^2 = .385$. Participants showed a generally larger proprioceptive drift in VR compared to the real environment (10.2 cm vs. 7.6 cm). There was also a significant main effect of SYNCHRONY, $F(1,23) = 6.591$, $p = .017$, $\eta_p^2 = .222$, indicating a higher proprioceptive drift in the synchronous conditions compared to the asynchronous conditions (9.7 cm vs. 8.1 cm). However, there was no significant interaction effect of ENVIRONMENT $\times$ SYNCHRONY, $F(1,23) = 0.139$, $p = .712$, $\eta_p^2 = .006$. The non-significant interaction effect ENVIRONMENT $\times$ SYNCHRONY revealed by the ANOVA does not automatically confirm the hypothesis that the difference in proprioceptive drift between the *synchronous* condition and the *asynchronous* condition is comparable between environments. Therefore, to quantify the comparability of the effects between VR and the real world, we calculated a Bayesian t-test on the differences between the proprioceptive drift in the *synchronous* condition and the *asynchronous* condition for both settings (Wagenmakers et al., 2018): $\Delta PropDrift = PropDrift_{sync} - PropDrift_{async}$. This revealed a Bayes factor of $BF_{01} = 4.371$, indicating that the data is 4.37 times more likely under the null hypothesis postulating identical RHI effects on proprioceptive

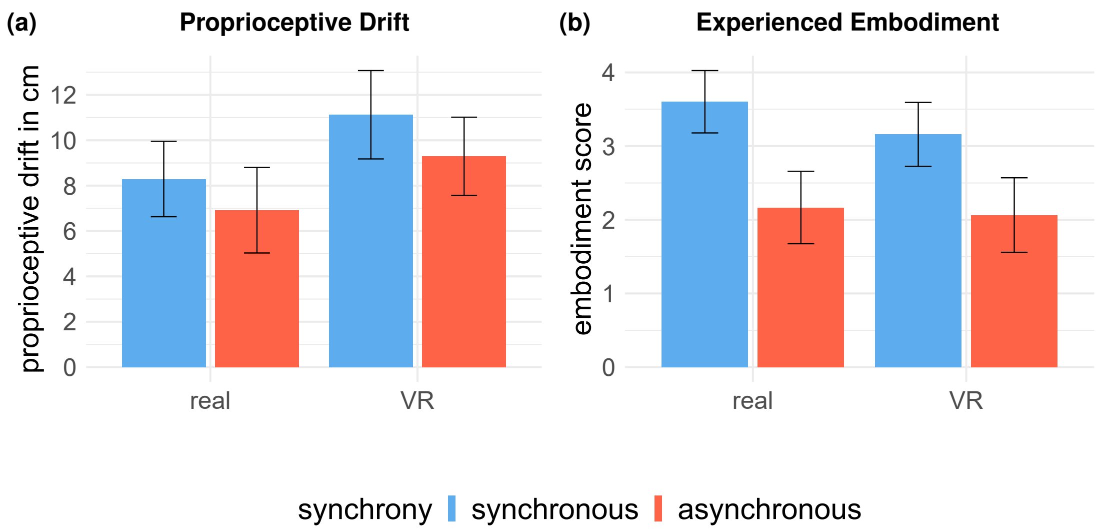

Figure 3.2: Average proprioceptive drift in cm (a) and the mean values of the dimension embodiment from the RHI questionnaire ranging from 0 to 6 (b) for the RHI performed in the real world and in VR. The error bars show the 95% confidence interval.

drift for VR and the real environment ($\Delta PropDrift_{VR} = \Delta PropDrift_{real}$) than under the alternative hypothesis that postulates different effects ($\Delta PropDrift_{VR} \neq \Delta PropDrift_{real}$). Figure 3.2a depicts the mean ratings of the proprioceptive drift.

3.3.2 RHI Questionnaire

We performed 2(ENVIRONMENT: *real* vs. *VR*) $\times$ 2(SYNCHRONY: *synchronous* vs. *asynchronous*) ANOVAs on each dimension of the RHI questionnaire. Figure 3.2b shows the mean ratings of the dimension *embodiment of the rubber hand* and Figure 3.3 shows the mean ratings of the dimensions *loss of own hand*, *movement*, *affect*, and *deafference* of the RHI questionnaire.

3.3.2.1 Embodiment of the Rubber Hand

There was no significant effect of ENVIRONMENT, $F(1,23) = 4.099$, $p = .054$, $\eta_p^2 = .151$, on the dimension *embodiment of the rubber hand*. However, we found a significant effect of SYNCHRONY, $F(1,23) = 43.443$, $p < .001$, $\eta_p^2 = .653$, indicating that participants experienced higher embodiment of the rubber hand in the synchronous conditions compared to the asynchronous conditions. There was no significant interaction

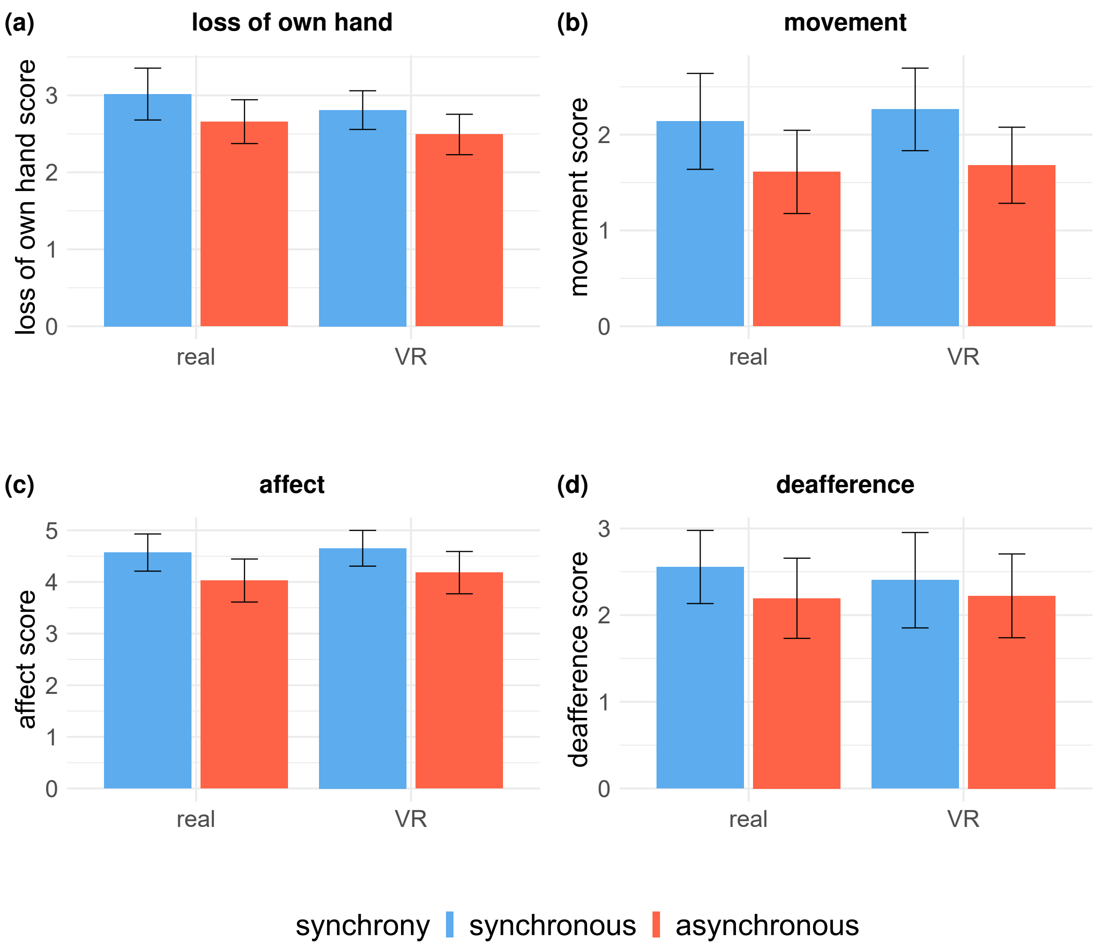

Figure 3.3: Mean values of the dimensions loss of own hand (a), movement (b), affect (c), and deafference (d) from the RHI questionnaire ranging from 0 to 6 for the RHI performed in the real world and in VR. The error bars show the 95% confidence interval.

effect of ENVIRONMENT × SYNCHRONY, $F(1,23) = 1.736$, $p = .200$, $\eta_p^2 = .070$. To quantify the comparability of the effects between VR and the real world, we calculated a Bayesian t-test on the differences between the difference in the dimension *embodiment of the rubber hand* in the *synchronous* condition and the *asynchronous* condition for both settings (Wagenmakers et al., 2018). This revealed a Bayes factor of $BF_{01} = 2.162$, indicating that the data is 2.16 times more likely under the null hypothesis postulating identical RHI effects on *embodiment of the rubber hand* for VR and the real environment than under the alternative hypothesis that postulates different effects.

3.3.2.2 Loss of Own Hand

There was no significant effect of ENVIRONMENT, $F(1,23) = 2.094$, $p = .161$, $\eta_p^2 = .083$, on the dimension *loss of own hand*. However, we found a significant effect of SYNCHRONY, $F(1,23) = 9.224$, $p = .005$, $\eta_p^2 = .286$, on the dimension *loss of own hand*, indicating that participants experienced a stronger loss of control of their own hand in the synchronous conditions compared to the asynchronous conditions. There was no significant interaction effect of ENVIRONMENT $\times$ SYNCHRONY, $F(1,23) = 0.064$, $p = .802$, $\eta_p^2 = .002$. A Bayes factor of $BF_{01} = 4.524$ indicated that the data is 4.52 times more likely under the null hypothesis postulating identical RHI effects on *loss of own hand* for VR and the real environment than under the alternative hypothesis that postulates different effects.

3.3.2.3 Movement

There was no significant effect of ENVIRONMENT, $F(1,23) = 0.289$, $p = .595$, $\eta_p^2 = .012$, on the dimension *movement*. However, we found a significant effect of SYNCHRONY, $F(1,23) = 7.951$, $p = .009$, $\eta_p^2 = .256$, on the dimension *movement*, indicating that participants experienced a higher shift in location of the own hand and the rubber hand in the synchronous conditions compared to the asynchronous conditions. There was no significant interaction effect of ENVIRONMENT $\times$ SYNCHRONY, $F(1,23) = 0.032$, $p = .857$, $\eta_p^2 = .001$, on the dimension *movement*. A Bayes factor of $BF_{01} = 4.589$ indicated that the data is 4.58 times more likely under the null hypothesis postulating identical RHI effects on *movement* for VR and the real environment than under the alternative hypothesis that postulates different effects.

3.3.2.4 Affect

There was no significant effect of ENVIRONMENT, $F(1,23) = 1.276$, $p = .270$, $\eta_p^2 = .052$, on the dimension *affect*. However, we found a significant effect of SYNCHRONY, $F(1,23) = 21.371$, $p < .001$, $\eta_p^2 = .481$, on the dimension *affect*, indicating that participants had a more enjoyable and interesting experience in the synchronous conditions compared to the asynchronous conditions. There was no significant interaction effect of ENVIRONMENT $\times$ SYNCHRONY, $F(1,23) = 0.061$, $p = .805$, $\eta_p^2 = .002$, on the dimension *affect*. A Bayes factor of $BF_{01} = 4.529$ indicated that the data is 4.52 times more likely under the null hypothesis postulating identical RHI effects on *affect* for VR and the real environment than under the alternative hypothesis that postulates different effects.

3.3.2.5 Deafference

We did not find a significant effect of ENVIRONMENT, $F(1,23) = 0.223$, $p = .640$, $\eta_p^2 = .009$, and of SYNCHRONY, $F(1,23) = 2.337$, $p = .139$, $\eta_p^2 = .092$, on the dimension *deafference*. There was no significant interaction effect of ENVIRONMENT × SYNCHRONY, $F(1,23) = 0.512$, $p = .481$, $\eta_p^2 = .021$, on the dimension *deafference*. A Bayes factor of $BF_{01} = 3.693$ indicated that the data is 3.69 times more likely under the null hypothesis postulating identical RHI effects on *deafference* for VR and the real environment than under the alternative hypothesis that postulates different effects.

3.3.2.6 Perceived Change in Temperature

To explore whether the participants perceived a change in skin temperature, we included the item *perceived change in temperature* in the statistical analysis. We did not find a significant effect of ENVIRONMENT, $F(1,23) = 0.064$, $p = .802$, $\eta_p^2 = .002$, and of SYNCHRONY, $F(1,23) = 0.258$, $p = .616$, $\eta_p^2 = .011$, on the item *perceived change in temperature*. There was no significant interaction effect of ENVIRONMENT × SYNCHRONY, $F(1,23) = 1.150$, $p = .294$, $\eta_p^2 = .047$. A Bayes factor of $BF_{01} = 2.785$ indicated that the data is 2.78 times more likely under the null hypothesis postulating identical RHI effects on *perceived change in temperature* for VR and the real environment than under the alternative hypothesis that postulates different effects.

3.3.2.7 Correlation Analysis of the Proprioceptive Drift and the Dimensions of the RHI Questionnaire

To test whether there is a relationship between the proprioceptive drift and the experienced embodiment of the rubber hand, we performed a Pearson's correlation analysis of the dimensions of the RHI questionnaire and the proprioceptive drift in the *synchronous* conditions. We did not find a significant relationship between proprioceptive drift and the dimensions *embodiment of the rubber hand*, *loss of own hand*, *movement*, and *deafference* of the RHI questionnaire (all $p > .05$). However, there was a significant positive correlation between the proprioceptive drift and the dimension *affect*, $r(46) = .333$, $p = .020$.

3.3.3 Skin Temperature

As previous work found that a drop in skin temperature was caused by the embodiment of the rubber hand and, thereby, only occurred in the stimulated hand and not in the unstimulated hand (Moseley et al., 2008), we evaluated the time course of the temperature difference between the right hand (stimulated) and the left hand (unstimulated) across the entire stroking procedure (see Figure 3.4). Additionally, we analyzed the absolute skin temperature of the right (stimulated) and left hand (unstimulated) across time (see Figure 3.5). In line with Moseley et al. (2008), we calculated 30-second time intervals and included the factor TIME with six levels (*0.5* vs *1* vs *1.5* vs *2* vs *2.5* vs *3*) in the statistical analyses.

3.3.3.1 Skin Temperature Difference between Both Hands

We performed a 2(ENVIRONMENT: *real* vs. *VR*) $\times$ 2(SYNCHRONY: *synchronous* vs. *asynchronous*) $\times$ 6(TIME: *0.5* vs *1* vs *1.5* vs *2* vs *2.5* vs *3*) ANOVA with repeated measures to analyze the skin temperature differences over the course of time: $\Delta t = t(\textit{stimulated hand}) - t(\textit{unstimulated hand})$. We did not find a significant main effect of ENVIRONMENT, $F(1,23) = 0.581$, $p = .453$, $\eta_p^2 = .024$, of SYNCHRONY, $F(1,23) = 0.704$, $p = .409$, $\eta_p^2 = .029$, and of TIME, $F(5,115) = 2.074$, $p = .073$, $\eta_p^2 = .082$. However, we found a significant interaction effect of SYNCHRONY $\times$ TIME, $F(5,115) = 4.829$, $p < .001$, $\eta_p^2 = .173$, indicating that the skin temperature differences between both hands over the course of time depended on the synchrony of stroking. We did not find interaction effects of ENVIRONMENT $\times$ SYNCHRONY, $F(1,23) = 0.048$, $p = .827$, $\eta_p^2 = .002$, of ENVIRONMENT $\times$ TIME, $F(5,115) = 0.185$, $p = .967$, $\eta_p^2 = .007$, as well as of ENVIRONMENT $\times$ SYNCHRONY $\times$ TIME, $F(5,115) = 0.360$, $p = .874$, $\eta_p^2 = .015$.

3.3.3.2 Correlation Analysis of the Proprioceptive Drift and the Skin Temperature Difference

We performed a Pearson's correlation analysis of the proprioceptive drift and the skin temperature difference to test whether there is a relationship between both measures in the last minute (the third minute) in the *synchronous* conditions. However, we did not find a significant relationship between the skin temperature difference between both hands and the proprioceptive drift, $r(46) = .078$, $p = .596$.

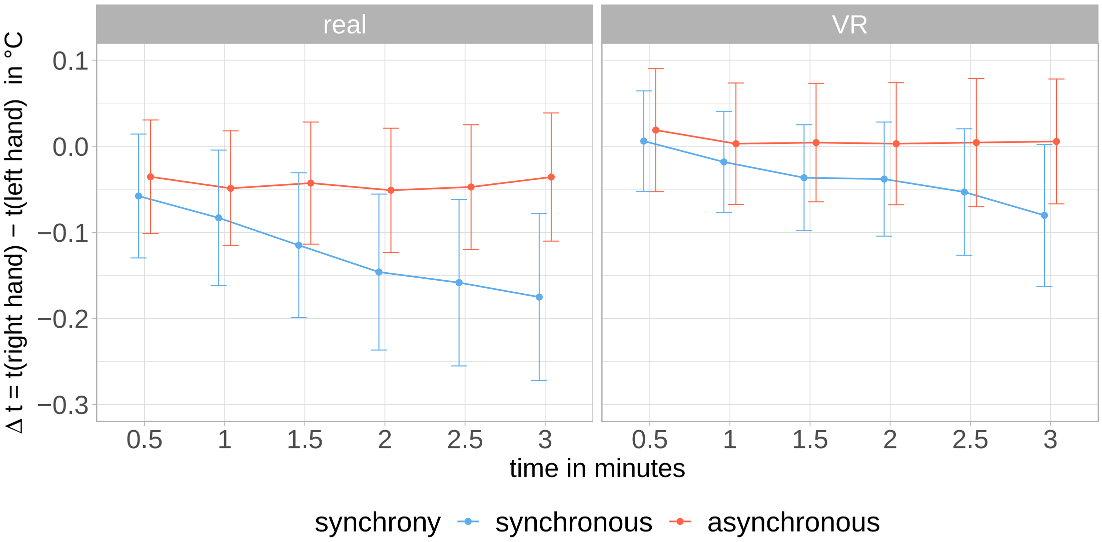

Figure 3.4: Average temperature difference (Δt) between the right (stimulated) and left hand (unstimulated) per 30 seconds during the RHI in the real world and in VR for synchronous and asynchronous stroking. The error bars show the standard error.

3.3.3.3 Correlation Analysis of the Dimensions of the RHI Questionnaire and the Skin Temperature Difference

We performed a Pearson's correlation analysis of each dimension of the RHI questionnaire and the skin temperature difference to test whether there is a relationship between both measures in the last minute (the third minute) in *synchronous* conditions. There was also no significant relationship between the dimensions *embodiment of the rubber hand*, *loss of own hand*, *movement*, *affect*, and *deafference* of the RHI questionnaire and the skin temperature difference between both hands (all $p > .05$).

3.3.3.4 Absolute Skin Temperature

We performed a 2(ENVIRONMENT: *real* vs. *VR*) × 2(SYNCHRONY: *synchronous* vs. *asynchronous*) × 6(TIME: *0.5* vs *1* vs *1.5* vs *2* vs *2.5* vs *3*) × 2(HAND: *left hand* vs *right hand*) ANOVA with repeated measures on the absolute skin temperature of the left hand (unstimulated) and right hand (stimulated). We therefore included the factor HAND into the statistical analysis. There was no significant main effect of ENVIRONMENT, $F(1,23) = 0.021$, $p = .885$, $\eta_p^2 = .000$, of SYNCHRONY, $F(1,23) = 0.204$, $p = .655$, $\eta_p^2 = .008$, and of HAND, $F(1,23) = 0.347$, $p = .561$, $\eta_p^2 = .014$. However, we found a

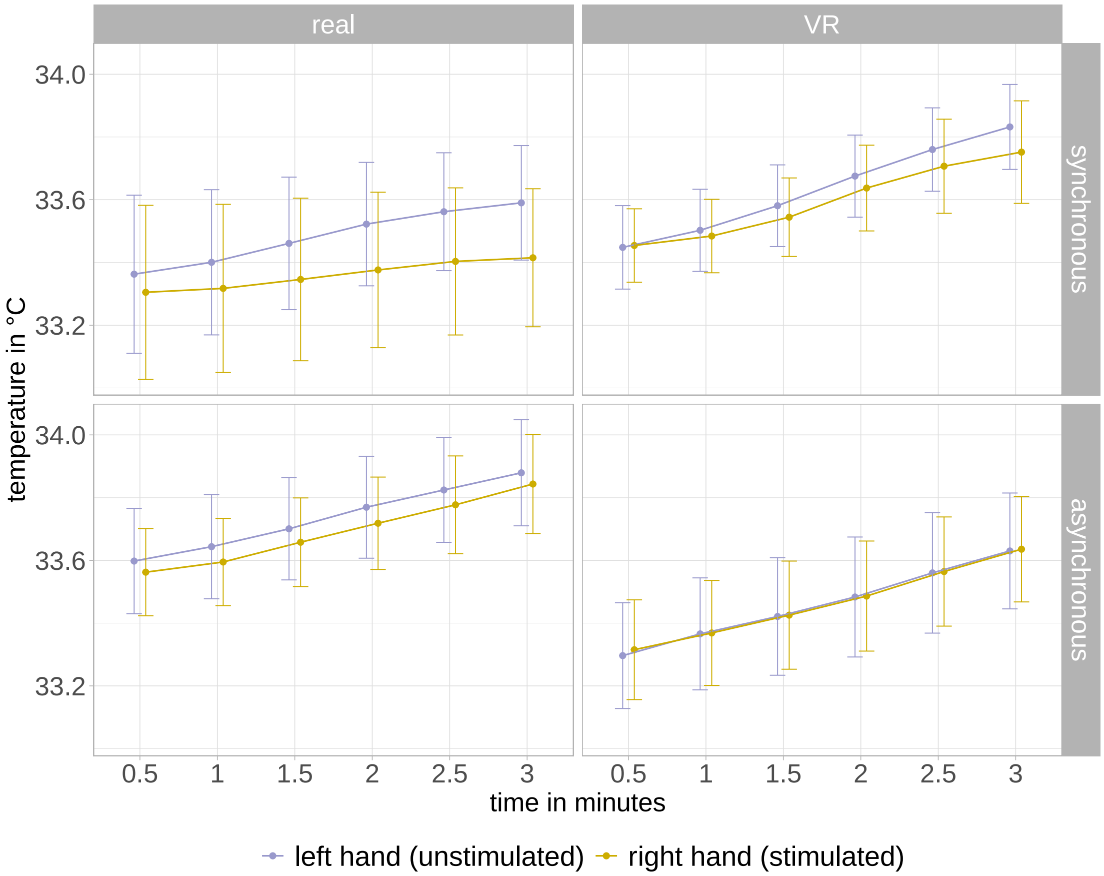

Figure 3.5: Average temperature per 30 seconds during the RHI in the real world and in VR for synchronous and asynchronous stroking for the left (unstimulated) and right hand (stimulated), respectively. The error bars show the standard error.

significant main effect of TIME on the absolute skin temperature, $F(5,115) = 27.835$, $p < .001$, $\eta_p^2 = .547$, indicating that the skin temperature of both hands increased over the course of time in all conditions. There was also an interaction effect of ENVIRONMENT × TIME, $F(5,115) = 2.666$, $p = .025$, $\eta_p^2 = .103$, indicating that the time course of the skin temperature of both hands was different in VR compared to the real world. We also found an interaction effect of SYNCHRONY × HAND × TIME, $F(5,115) = 4.829$, $p < .001$, $\eta_p^2 = .173$, indicating that the time course of the skin temperature depended on the hand and the synchrony of stroking. Other interaction effects were not significant (all $p > .05$).

3.3.3.5 Correlation Analysis of the Proprioceptive Drift and the Absolute Skin Temperature

We performed a Pearson's correlation analysis of the proprioceptive drift and the absolute skin temperature of the right hand (stimulated) to test whether there is a relationship between both measures in the last minute (the third minute) in the *synchronous* conditions. We did not find a significant relationship between the absolute skin temperature of the right hand and the proprioceptive drift, $r(46) = .228$, $p = .118$.

3.3.3.6 Correlation Analysis of the dimensions of the RHI Questionnaire and the Absolute Skin Temperature

We performed a Pearson's correlation analysis of each dimension of the RHI questionnaire and the absolute skin temperature of the right hand (stimulated) to test whether there is a relationship between both measures in the last minute (the third minute) in the *synchronous* conditions. There was no significant relationship between all dimensions of the RHI questionnaire and the absolute skin temperature of the right hand (all $p > .05$).

3.4 Discussion

Our analysis of objective and subjective measures indicates that we successfully induced the RHI in the real world as well as in VR. As predicted, for both environments, participants had a higher proprioceptive drift during synchronous stroking compared to asynchronous stroking. Consequently, they underestimated the distance between the physical or virtual rubber hand and their real hand while being stroked synchronously. In VR, the proprioceptive drift was generally higher compared to the real world. As indicated by questionnaire ratings, we found that the participants experienced a stronger RHI during synchronous stroking in both environments. Our results also revealed that the RHI affected the skin temperature of the own hands. Even if the skin temperature of both hands increased in all conditions, the interaction between SYNCHRONY and TIME indicates that skin temperature difference between the right (stimulated) and left (unstimulated) hand increasingly diverge from each other over time due to synchronous stroking (see Figure 3.4). Hence, there was a lower increase in the skin temperature of the stimulated hand compared to the increase in skin temperature of the unstimulated hand. This attenuated increase in skin temperature of the stimulated hand only occurred when the real hand and the rubber hand were stroked synchronously. During asynchronous stroking, the temperature differences between both hands remained constant over time. Furthermore, the time course of the absolute skin temperature varied between both environments. Overall, our findings show that the effects caused by a physical and virtual RHI are comparable. However, there are measurable differences between both environments that have to be considered when inducing BOIs in VR.

3.4.1 Physical RHI vs Virtual RHI

We found systematic effects of the RHI performed in the real world and in VR on the proprioceptive drift and the questionnaire ratings. In line with findings from RHI experiments (e.g., Erro et al., 2020; Tsakiris & Haggard, 2005; Wold et al., 2014), we found a significant higher proprioceptive drift as well as significant higher scores for each dimension of the RHI questionnaire during synchronous stroking compared to asynchronous stroking. However, the proprioceptive drift was generally higher in the RHI conducted in VR compared to the real world. This is not necessarily an implicit indicator for a higher degree of ownership of the virtual rubber hand in VR. Instead, other factors such as a reduced field of view due to the HMD or a different depth perception in VR could be responsible for such effects (Vienne et al., 2020). This assumption may be supported by the fact that we could not find significant differences between the effects of both environments on the ratings of the RHI questionnaire. However, we did not find any correlation between the perceived embodiment assessed by questionnaire ratings and the proprioceptive drift. This is not surprising as previous investigations found that both measures are not necessarily related to each other due to different underlying mechanisms (Rohde et al., 2011; van Stralen et al., 2014). Nonetheless, we cannot rule out that the embodiment of a virtual rubber hand causes a stronger misperception of the own hand's perceived location.

When being immersed in VR, not only is the user's hand "replaced" by the virtual rubber hand but the entire body by the virtual body. In other words, in VR the participants did not only experience a limb ownership illusion of the rubber hand but also a full-body ownership illusion of the virtual body. This is in line with Llobera et al. (2013), who postulated that when participants enter the VR and perceive a VE from a first-person perspective, the virtual body substitutes the entire real body. Even if we covered the real and virtual body by a hairdressing cape to minimize all identity cues to ensure a high concordance between the real world and VR, small deviations between own body and virtual self can activate the illusion of embodiment. As we asked about the distance between the real hand and the virtual rubber hand to assess the proprioceptive drift, the position of the real hand, which is a part of the virtual body in VR, can already be misperceived resulting in a higher proprioceptive drift. Future studies should investigate whether multisensory asynchrony, e.g., caused by latency, breaks the illusion on full-body level or only on limb ownership.

For the proprioceptive drift and the ratings of the RHI questionnaire, we could not find an interaction effect of the environment in which the RHI was performed and the synchrony of stroking. However, this does not automatically confirm that the difference in proprioceptive drift and the dimensions of the RHI questionnaire between the *synchronous* condition and the *asynchronous* condition is comparable between environments. The calculated Bayes factors, however, showed anecdotal to moderate evidence ($BF_{01} >= 2.162$ and $BF_{01} <= 4.589$) that the data is more likely under the null hypothesis postulating identical RHI effects on the proprioceptive drift and the dimensions of the RHI questionnaire for VR and the real environment than under the alternative hypothesis that postulates different effects for both environments. This implies that the RHI resulted in comparable effects regardless of whether it was performed in the real world or in VR. Hence, our findings suggest that VR technology can be leveraged to create RHIs and increase our understanding of embodying virtual avatars.

Descriptive statistics show a systematic course of the skin temperature differences across time for the RHI performed in the real world and in VR. However, we found that the time course of the absolute skin temperature depended on the environment in which the RHI was performed. Hence, we cannot conclude that the virtual rubber hand in VR had the same impact on the users' skin temperature as the physical rubber hand in the real world. Even when the RHI was generally a novel experience for the participants, we assume that experiencing the RHI in VR even increased their excitement and interest. This novelty effect caused by VR could in turn influence the skin temperature (McFarland, 1985; Balters & Steinert, 2017) attenuating the effects caused by the embodiment of the virtual rubber hand. Additionally, the participants were wearing an HMD during the RHI in VR. This could also affect thermoregulation due to increased sweating while experiencing the RHI. As we did not analyze the participants' amount of sweat, future studies could investigate whether and to what extent sweating as a heat-regulatory function mediates the effects on skin temperature during bodily illusions in VR.

3.4.2 Effects on Skin Temperature

To explain the effects on skin temperature caused by the RHI, we refer to research from neuropsychology. In a series of studies, Moseley et al. (2008) revealed that the embodiment of the rubber hand caused a decrease in skin temperature of the own hand. Notably, the skin temperature of other body parts was unaffected, i.e., the other hand and the feet did not cool. Besides, the authors found that a stronger illusion of ownership caused a greater drop in skin temperature of the stimulated hand. This implies that the effects depended on the illusion of ownership of the rubber hand. The authors argued that embodying a rubber hand disrupts the sense of ownership of the own stimulated hand, which in turn affects autonomic temperature regulation processes. As a disruption of the human body's temperature regulation is also a characteristic of neurological disorders that are frequently connected with a dysfunctional sense of ownership of the own body (Priebe & Röhricht, 2001; Rogers & Ozonoff, 2005), e.g., patients suffering from somatoparaphrenia have the feeling that their affected limbs belong to someone else (van Stralen et al., 2013), researchers assume that during the RHI a process of "disownership" of the real limb occurs in a way as if it was "replaced" by the rubber hand (Moseley et al., 2008; Moseley et al., 2012).

Moseley et al. (2012) introduced the concept of the cortical body matrix to explain the effects of bodily illusions. The cortical body matrix is considered as a neural representation in the brain involving the body, the personal space, and the peripersonal space (near surrounding space around the body), which aims at maintaining the integrity of the body at homeostatic and psychological levels. The authors assume that the neural activity across the cortical body matrix is responsible for the effects on the skin temperature during the RHI. When the real and the rubber hand are stroked synchronously, the neural areas associated with the space occupied by the rubber hand increase their activity starting to incorporate it into the own body schema, which in turn results in the sensation of the rubber hand being a part of the actual body. On the contrary, the neural areas associated with the space around the real hand decrease their activity, which in turn decreases the extent to which the real hand is "owned" and eventually, results in reduced homeostatic controls, e.g., thermoregulation. As parts of the cortical body matrix have connections with parts in the brain that regulate autonomic functions, the authors assume that the blood flow to the "disowned" hand is reduced causing a drop in skin temperature. These explanations are in line with Barnsley et al. (2011), who showed that participants had an increased histamine reactivity in the stimulated hand during the RHI. As an elevated histamine reactivity is associated with a decreased response of the immune system resulting in reduced metabolism of histamine, the authors concluded that the stimulated hand during the RHI is treated as when it has been "rejected" (Barnsley et al., 2011).

Our results seem to confirm this astonishing psychophysiological impact of embodying artificial limbs such as a physical or virtual rubber hand. In contrast to Moseley et al. (2008), however, it is important to note that we did not induce a cooling of the stimulated hand in a sense that the skin temperature at the end was lower than at the beginning of the RHI. Instead, we found a constant increase in skin temperature of both hands regardless of the vividness of the experienced RHI (see Figure 3.5). This seemed to be the "normal" physiological response in our experiment, as the participants were engaged in a user study while sitting at the same table with the experimenter in our laboratory and being stroked for minutes. Hence, it seems plausible that the skin temperature during the experiment could increase. Although our laboratory is temperature-controlled, the environmental temperature directly around and within the experimental area could also possibly increase affecting the participants' skin temperature. Furthermore, we cannot dismiss thermal reactions caused by social contact through the touch of the experimenter (Hahn et al., 2012; de Haan et al., 2017; Rohde et al., 2013). Even if the skin temperature increased on both, the left hand (untouched), as well as the right hand (touched), the experience of being stroked by a person can cause a widespread increase in skin temperature of different body parts (Willemse, 2015).

In this case, the stroking of the experimenter would cause the skin temperature to increase (van Stralen et al., 2014). Rohde et al. (2013), for example, could only find a decreased skin temperature of the own hand during the RHI when the participants were stroked by a human experimenter instead of an automated stroking device. These results imply that the extent of the RHI, as well as the effects on skin temperature, seem to be modulated by the characteristics of stroking. Nonetheless, in our study, the temperature of the stimulated and unstimulated hand increasingly diverged across time during synchronous stroking (see Figure 3.4). During asynchronous stroking, such effects did not occur. We, therefore, assume that RHI decreased the skin temperature of the stimulated hand in the sense that it attenuated the "normal" increase in skin temperature that occurred in this situation under those circumstances. Considering the effect sizes found for the effects on the skin temperature, which can be interpreted as small, we deem that the effect of embodying a rubber hand on the skin temperature is not large enough to actually cool the hand in our experimental setting in a sense that the skin temperature is lower at the end of RHI than at the beginning. This is in line with Tieri et al. (2017) who documented that the RHI can evoke arousal that in turn outperforms effects caused by the embodiment of the rubber hand resulting in an increased skin temperature.

As we could not find a correlation between the skin temperature differences and the ratings of the RHI questionnaire as well as the proprioceptive drift, we cannot conclude that the embodiment of the physical or virtual rubber hand was responsible for a decreased temperature of the stimulated hand. In accordance to Folegatti et al. (2009), we, therefore, cannot dismiss that changes in skin temperature were caused by the perceptual conflict that is created during the RHI, i.e., the mismatch between the felt and seen tactile cues. Folegatti et al. (2009) used prismatic goggles to shift the perceived position of the real hand by 7.5 cm. By doing so, they could still induce a limb ownership illusion of the real hand resulting in a higher proprioceptive drift and questionnaire ratings during synchronous stroking compared to asynchronous stroking. In this case, skin temperature changes would not be a consequence of "disowning" the real hand. Instead, the visuo-proprioceptive conflict could cause physiological changes such as a decreased skin temperature. Due to these ambiguous findings, more research is required to gain a deeper understanding of the precise mechanisms underlying thermal reactions caused by the RHI.

We did not find any evidence that the participants could perceive a change in temperature. Moseley et al. (2008), however, documented that in their series of studies 17% of the participants reported that their stimulated arm felt cooler during the RHI. Due to the exploratory nature, we used only one own-created item to get a first insight into whether participants could notice any change in skin temperature. Hence, future studies should emphasize this aspect and investigate if such effects could be amplified in a way to enable users to experience a cooler skin temperature during bodily illusions, e.g., when embodying a full-body avatar (Salomon et al., 2013). Designers of immersive applications could potentially utilize this as part of the VR experience, e.g., for horror experiences or virtual simulations (Wu et al., 2019). However, this is rather speculative as a deeper understanding of this phenomenon is needed to be able to leverage it.

The effects of body (dis)ownership on skin temperature have been highly controversial in research. While some studies were able to find illusion-related effects on skin temperature (Moseley et al., 2008; Kammers et al., 2011; Tsakiris et al., 2011; Salomon et al., 2013; Hohwy & Paton, 2010), others were not (David et al., 2014; Rohde et al., 2013; de Haan et al., 2017; Grynberg & Pollatos, 2015; Paton et al., 2012; Thakkar et al., 2011). Due to the ambiguous findings from previous work, it seems that such effects can be easily confounded by other factors that have to be controlled throughout the experiment. As our results suggest that the RHI can affect the skin temperature of the own hand over time, we propose our experimental setting for further validation and suggest considering virtual and real world to induce such effects.

As previously mentioned, effects on skin temperature could not be found when the participants were stroked by an automated stroking device (Rohde et al., 2013). As the characteristics of the experimenter can also modulate the intensity of the experienced RHI (de Haan et al., 2017), we highly suggest concealing the presence of the experimenter while stroking the participants' hand. Future work could analyze whether wearing gloves to cover further identity cues such as the experimenter's gender could reduce the variance in the data. Furthermore, we recommend a continuous measurement of the skin temperature, as many studies assessed the skin temperature at certain points in time, e.g., before and after stroking (David et al., 2014). Continuously assessing the skin temperature allows obtaining valuable insights about the time course of the temperature. In our study, the participants were stroked for three minutes in each condition. Longer stroking periods as performed by Moseley et al. (2008) could then inform us how the temperature evolves over time and whether the induced attenuation keeps reducing the skin temperature. As recommended by van Stralen et al. (2014), we used a stroking velocity of ~3 cm/s that is usually perceived as more pleasant than faster stroking. This is in line with our results showing high ratings of the dimension *affect* of the RHI questionnaire indicating a positive experience (see Figure 3.3). Although our findings seem promising, more research is needed to better understand the effects of embodying a physical or virtual rubber hand on the skin temperature of the own hand. For this reason, future studies can build upon our work to further explore this phenomenon and analyze whether it is a reliable physiological response to bodily illusions under different conditions.

3.4.3 Implications and Future Work

Even though we found some differences between the effects of a physical and virtual RHI on the proprioceptive drift and the skin temperature, our results showed a consistent pattern across all conditions. Our investigation did not reveal any contradictory findings that indicate that the principles underlying the RHI are different in VR compared to the real world. Hence, we argue that the RHI can be transferred into VR resulting in similar and comparable effects. As VR serves an extended design space, it is possible to produce experiences that are hardly feasible or impossible to create in the real world. Researchers can, therefore, benefit from the sheer endless amount of design choices in VR. To learn about the limits of the brain's plasticity and human perception, virtual rubber hands, for example, with a reduced amount of fingers (Schwind et al., 2017a), with a burning skin (Eckhoff et al., 2021), or with a supernatural length (Kilteni et al., 2012) can be easily designed in a VE allowing a high degree of control over the experimental variables. Future work should validate other types of bodily illusions, such as full-body ownership illusions to gain a deeper knowledge about the embodiment of physical entities, e.g., mannequins (Petkova & Ehrsson, 2008) or virtual entities, e.g., a full-body avatar.

Regarding the effects on skin temperature, it is important to consider this phenomenon when creating embodied VR experiences. Researchers have to know how limb ownership illusions influence the basal skin temperature as such effects may confound physiological measurements, e.g., the skin conductance response (Lobstein & Cort, 1978). As the human body's temperature regulation processes involve thermal signals from the skin (Romanovsky, 2014), the activity of sweat glands therefore partially depends on the skin temperature (Lobstein & Cort, 1978). From an HCI perspective, the effects found in our study raise new questions that should be addressed in future work to gain further understanding of the mechanisms underlying the embodiment of virtual avatars. Skin temperature changes while being stroked may be relevant for CVEs. When the participants experienced ownership of a virtual hand with a rubbery appearance that differs from the own physical hand, the touches caused thermal reactions. In this vein, such effects may also be explained within the theoretical framework of the Proteus effect that describes behavioral, perceptual, and attitudinal changes caused by an avatar's stereotypical visual appearance (Yee & Bailenson, 2007).

The embodiment of a virtual hand whose rubbery appearance is associated with artificiality and inanimateness may potentially induce physiological changes. As our results and findings from previous work did not determine if the changes in skin temperature were either caused by a process of "disownerhsip" of the real hand or the embodiment of a hand with a rubbery appearance, future work should further explore such aspects related to the Proteus effect. Furthermore, as designers aim at establishing a feeling of having a body in the VE to create a realistic and embodied VR experience, a drop in skin temperature has to be taken into account when embodying virtual avatars. Finger dexterity, for example, is affected by the temperature of the fingers and the hand (Chen et al., 2010). Hence, it is important to better understand the physiological consequences of embodying virtual avatars in VR, as a decreased skin temperature could even have detrimental effects on the users' performance while interacting with the VE.

3.5 Conclusion

In this chapter, we compared the RHI in the real world with a RHI in VR. We, therefore, systematically designed a virtual replica of the real environment to reproduce the RHI paradigm in VR. We then conducted a study with 24 participants who experienced the RHI in the real world and in VR. The proprioceptive drift, as well as the ratings of the RHI questionnaire, were higher during synchronous stroking compared to asynchronous stroking in both environments. The proprioceptive drift was generally higher in VR than in the real world. However, equivalent tests using the Bayes factor revealed that the differences between the effects on the proprioceptive drift caused by synchronous stroking and asynchronous stroking were more likely identical for both environments. This could also be shown for the effects on the ratings of the RHI questionnaire. Although these findings do not prove that a physical RHI is the same as a virtual RHI, they still imply that the RHI causes similar and comparable effects in both environments. Hence, this work validates that the RHI can be leveraged in VR to increase our understanding of BOIs and the virtual embodiment of avatars.

We also found that the RHI affected the skin temperature of the real hands. Even if the skin temperature of both hands increased, the skin temperature of the right hand (stimulated) and the left hand (unstimulated) increasingly diverged from each other across time during synchronous stroking. Hence, the increase in skin temperature of the stimulated hand was lower compared to the increase in skin temperature of the unstimulated hand. During asynchronous stroking, the temperature differences between both hands remained constant across time. The findings, therefore, suggest that the RHI can affect thermoregulation causing changes in skin temperature of the own hand. In line with theories from neuropsychology, we assume that a process of psychological "disownership" of the own hand may be responsible for such effects. These insights extend our knowledge about the consequences of limb ownership illusions for the own body and illustrate the psychophysiological impact of embodying virtual limbs on users.

More research is required to confirm the congruence between RHI effects in both environments and find out if changes in skin temperature are a reliable physiological response. Hence, future studies can build upon our work to further explore this and other related phenomena to gain a deeper knowledge about the mechanisms underlying bodily illusions, so that this knowledge can be used to create more realistic and immersive VR applications.

4

Effects of Altered Body Structures

In the previous chapter, we conducted the seminal RHI to learn about BOIs and the perceptual and physiological consequences for the users. Additionally, we learned how we can induce a sense of embodying an artificial hand through synchronous visuo-tactile stimulation. During the virtual RHI, the users only observed the rubber hand being touched but did not actively interact with the VE. Typically, however, users are actively involved in VR and explore the surrounding VE using their virtual body. From an HCI perspective, it is important to allow users to move their virtual hands in VR without being limited to only passively observing the virtual limbs. In this chapter, we, therefore, induce ownership of virtual hands using visuo-motor synchrony via hand tracking. In particular, we aim at learning more about the effects on users' behavior and perception by changing the visual appearance of the virtual hands.

Inspired by stylized cartoon characters with less than five fingers from animated movies and video games, we, therefore, manipulated the realism of the virtual hands and changed the anatomy by removing individual fingers. If avatars with altered body structures were accepted and did not negatively affect the interaction in VR, such changes could be promising to induce behavioral changes and allow users to experience how it feels to embody avatars with characteristics that deviate from human anatomy. We found that the removal of individual fingers (particularly dominant fingers such as the index finger and the thumb) could decrease the sense of presence and caused phantom pain. These adverse effects were even larger at high levels of realism. Our results also indicate that users' behavior and way of interacting with the VE were affected by the visual appearance of the virtual hands. We discuss these findings in the context of avatars with altered body structures and the Proteus effect.

This chapter is based on the following publication:

Kocur, M., Graf, S., & Schwind, V. (2020b). "The Impact of Missing Fingers in Virtual Reality." In: *26th ACM Symposium on Virtual Reality Software and Technology*. VRST '20. Virtual Event, Canada: Association for Computing Machinery, pp. 1–5. ISBN: 9781450376198. DOI: 10.1145/3385956.3418973.

4.1 Background and Research Rationale

Hands and fingers belong to the most important parts of one's own body as they are being used for motor control, touch, and haptic sensations. Visible in the field of view of the user, hands and fingers are often being rendered in VR applications to provide both an intuitive controlling interface as well as an immersive experience. Recent VR systems can place hands and fingers using sensors of game controllers or even track them without wearing additional hardware or markers. However, an avatar does not necessarily have to look human-like (Lin & Jörg, 2016; Lugrin et al., 2015; Yuan & Steed, 2010) or do not necessarily have to match the human body structure (Hoyet et al., 2016; Schwind et al., 2017a).

Character designers of games and immersive applications often stylize their avatars or refer to existing content. Four-fingered alien characters, for example, in *James Cameron's Avatar – The Game* (Ubisoft, 2009) are designed according to the designs of the movie. Characters in the *LEGO computer game series* (The Lego Group, 1995) have hands in the form of brackets such as the toy figures by LEGO. Altered body structures can also be found by designs from cartoonists who sometimes reduce the number of fingers in their character drawings to avoid too big hand drawings or overlapping of their outlines due to the thickness of their pen strokes, e.g., *The Smurfs Game Series* (Peyo, 1982), *The Simpsons Game* (Selman et al., 2007), or *Crash Bandicoot* (Gavin & Rubin, 1996).

However, little is known about the effects of avatars with altered body structures on the user in VR. Previous work found that the number of missing fingers negatively correlates with the degree of presence (Schwind et al., 2017a). The higher the realism of the virtual embodiment and the more fingers are missing, the lower the sensation of presence. Very abstract avatars with a reduced number of fingers do not seem to negatively affect presence, as their appearance is less associated with a limb loss of one's own body. However, quantitative findings about the effects of individually removed fingers and their importance while experiencing presence or phantom pain sensations are yet unknown.

Visually removing individual fingers can induce behavioral changes, however, it is also unknown which fingers are being used instead. A comparison of relative finger usage allows inferring their importance in HCI and an easier mapping of hand interaction with hands that have fewer fingers. Thus, a systematic behavioral change among fingers can help designers and developers to optimize the mapping of virtual avatars with altered hand structures. This research contributes to an understanding of visuo-motor integration and a step towards the quantification of limb ownership using an objective measure. As previous work already suggests that realism could not only affect presence but also trigger behavioral changes, it is further important to investigate if the effects of finger loss depend on the similarity to the human body. Therefore, researchers and designers of VR applications need to know about the impact of altered body structures on users in VR to be able to utilize them to enhance the user experience or even to avoid undesired effects that negatively affect the overall VR experience.

4.2 Method

As we learned in previous chapters, the brain uses semantic knowledge about the human body structure to incorporate perceived limbs into the own body schema. Due to the importance and usage of virtual hands in immersive VR applications, we investigate if individual missing fingers differently affect the sense of presence and phantom pain perception, and if their usage potentially depends on the realism of the avatar. As we learned that the visual appearance of avatars can induce behavioral changes, we hypothesize that users' behavior and interaction in the VE is affected by the virtual hands' appearance and missing fingers. How other limbs potentially compensate for the usage of missing fingers is currently unknown, however, important for virtual character designs and mappings of hand avatars with altered body structures. As a reduced number

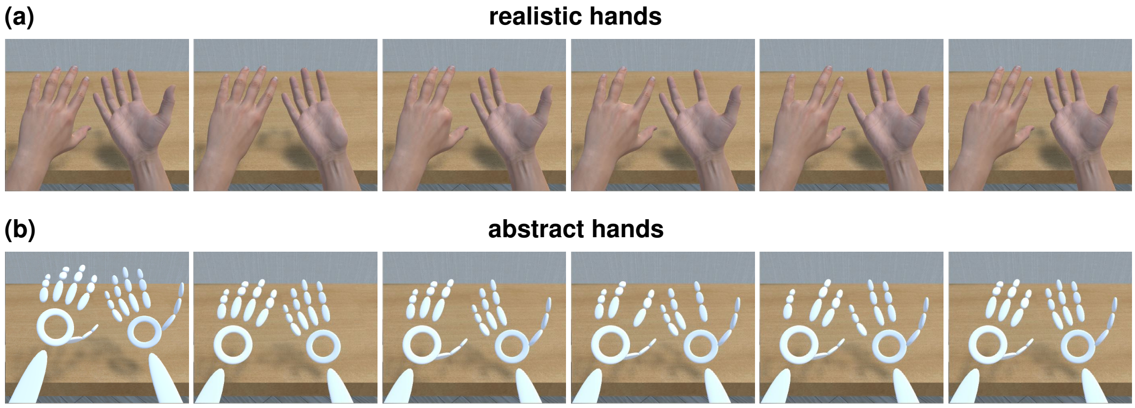

Figure 4.1: Models of the realistic (a) and abstract (b) hand pairs. Fingers are either all visible, without thumb, without index finger, without middle finger, without ring finger, or without little finger (from left to right).

of fingers decreases presence while using realistic avatars (Schwind et al., 2017a), we hypothesize that interaction effects between individual missing limbs and avatar realism will occur.

4.2.1 Study Design

We used a within-subjects design with the two independent variables FINGERS (*all fingers*, *missing thumbs*, *missing index fingers*, *missing middle fingers*, *missing ring fingers*, *missing little fingers*) and REALISM (*abstract* and *realistic*) resulting in 12 conditions. We collected quantitative data using questionnaires in VR as suggested by previous research indicating that surveying participants during the VR experience reduces the variance of presence scores (Schwind et al., 2019).

4.2.2 Stimuli

The virtual avatar hand pairs used in this study are based on previous work and the project files provided by Schwind et al. (2017a)[1]. In their work, the authors *successively* removed fingers. We *individually* removed them on a human as well as on an abstract hand to understand if the effects of missing fingers depend on virtual realism. All hands used the same virtual hand rig and fingertips as colliders for interactions. As it was necessary to measure finger usage even when they were missing, all five fingers were

[1] `https://github.com/valentin-schwind/lessfingers`

Figure 4.2: Participants in the real world (top) and their avatars in VR (bottom) playing the keyboard, turning dice, and completing the virtual questionnaire.

able to trigger interactions at any time. To avoid gender mismatches (Schwind et al., 2017b), we used an androgynous hand model without explicit gender cues for realistic hand pairs for male and female participants. Fingers phalanges were removed using Autodesk 3ds Max by a professional 3D artist. Abstract hands are based on previous work (Schwind et al., 2017a; Schwind et al., 2017b; Argelaguet et al., 2016) and consist of rigid shapes for the fingers and arms as well as a circle-shaped palm. Figure 4.1 shows the virtual hand pairs used in the study.

4.2.3 Measures

As already mentioned, we surveyed participants using questionnaires in VR after each condition to reduce potential score variances and to enable a smooth user experience without leaving the VR. As the Igroup Presence Questionnaire (IPQ) by Schubert et al. (2001) seems to best reflect the construct of presence among other established questionnaires in VR (Schwind et al., 2019), we used their 14-items questionnaire correspondingly. Thus, the participants completed the questionnaires using the virtual hand pairs whose effects we measured. Every item was presented on a virtual panel in front of the participants. To assess their perceived phantom pain perception, we used the Visual Analog Scale (VAS) as a psychometric response. The VAS is a common measurement instrument to assess (phantom) pain perception in clinical studies (Hawker et al., 2011; Reips & Funke, 2008;

Grant et al., 1999). We explicitly asked participants to rate their pain perception *related to their hands* using a continuous slider with the two endpoints “no pain” and “worst possible pain”. In addition to the subjective measures, we measured the frequency of finger collisions with the virtual objects to determine finger usage. All fingers (including the missing ones) received virtual colliders, which registered an intersection with the 3D target objects (dice, keyboard, and user interface elements of the questionnaires). As already mentioned, fingertip colliders were also used to trigger interactions. Collisions with the virtual table or any other objects within the scene were not considered in the analysis.

4.2.4 Tasks

Two tasks were designed to facilitate an immersive VR experience with the virtual hands in the field of view of the user during each condition. Tasks were inspired by previous work (Schwind et al., 2017a; Schwind et al., 2017b) engaging users to directly interact with the virtual objects. As all fingers could be used to solve those tasks, participants were free to choose which hands and which fingers they wanted to use (see Figure 4.2).

In the *keyboard task*, we asked participants to play sounds on a virtual piano. Black and white keys during the task were randomly illuminated and had to be pressed to play a sound. Participants could use all their fingers but not at the same time as only one button was illuminated at the same time. As participants had different prior experiences in piano play, the task was also used to investigate the effect of trained behavior on finger usage. Thus, we asked participants if they had previous long-term motor practice in piano play with 10 fingers.

In the *turning dice* task, the participants had to rotate three hand-sized cubes with numbered faces and lay them correctly on the virtual table in front of them. Numbers on the upper sides of the cubes had to match a random sequence of three numbers on the virtual display behind the table. It was not predetermined in which order the participants put the dice on the table and how they turned them (e.g., through taking into a hand or throwing). However, due to the physics engine of Unity, multiple fingers had to be used at the same time to grab a cube and to turn the correct number upward.

Each task lasted one minute. As finger and hand interaction obviously depend on the activity, both tasks only reflect a specific use case of hand and finger interaction with a VR interface. As current VR interfaces typically provide no physical touch with the own body, we assume that finger usage in the real world differs from virtual interactions, per se. Thus, interactions in VR are inherently specific use cases for hand and finger usage, and our study cannot provide a general model of visual-haptic integration during hand interactions with fewer fingers.

4.2.5 Apparatus

Our application was developed using the Unity3D game engine (v. 2019.3.8f). We used an Oculus Rift CV1 (Oculus, Irvine, USA) as HMD and a Leap Motion sensor (Leap Motion Inc., San Francisco, USA) for hand tracking. The Leap Motion sensor was attached using a 3D printed frame at the front of the HMD. Our software ran on a PC with Windows 10, an Intel i7-8750H, 16GB RAM, and an NVIDIA GeForce GTX 1060 graphics card. The target frame rate of the application was 90 FPS while global illumination, anti-aliasing, and ambient occlusion were enabled. The virtual scene was a white room with a wooden table on which the tasks were performed. The participant in the real world sat on a chair during the experience in our laboratory as shown Figure 4.2.

4.2.6 Procedure

After welcoming the participants, we explained the purpose and course of the study, gave them a brief introduction about the apparatus, and asked them to sign an informed consent form and to complete a demographic questionnaire. We explicitly highlighted that participants could perceive sensations of phantom pain and withdraw or discontinue participation at any time without penalty or losing their compensation. After reading and signing the consent form, every participant was asked to take a seat in the middle of our VR laboratory (see Figure 4.2). We explained the functionality of the HMD as well as the hand tracking sensor. Condition order was given by a 12×12 balanced Latin square design. Participants started after a one-minute phase of familiarization with the first condition. The first task was playing the keyboard lasting one minute, followed by the turning dice task lasting another minute. After completing all conditions, participants had the opportunity to provide general feedback.

4.2.7 Participants

We recruited a total of 24 participants (14 female, 10 male) through our university's mailing list. Mean age of the participants was 23.25 ($SD = 4.16$) and ranged from 19 to 39 years, 16 were students in computer science, six in the humanities, one in medicine, and one in chemistry. We had 17 right-handed and seven left-handed participants in our study, 17 participants stated to have previous VR experience, seven none. All participants had light skin tones matching the visual appearance of the realistic virtual hand pairs. A total of 14 participants stated to have eye corrected vision, four were left- and 10 were right-handed. A number of 10 participants stated that they have learned piano play with 10 fingers, only one of the piano players was left-handed. None of them stated to suffer from any mental or physical disabilities. All participants were compensated with credits points for their study course. The study received clearance according to the ethics and privacy regulations of our institution.

4.3 Results

Shapiro-Wilk test of normality was used to investigate the assumption of normal distribution of all measures. The results indicated non-trivial violations of normality among multiple groups between all indices ($p < .05$). Thus, we applied an Aligned Rank Transform (ART) ANOVA for non-parametric multiple factor analyses using the ARTool package for R by Wobbrock et al. (2011) for hypothesis testing. Participant was entered as a random factor in all analyses. All pairwise post-hoc comparisons are Bonferroni-corrected.

4.3.1 Presence

A two-way repeated-measures ANOVA revealed a significant main effect of FINGERS, $F(5,253) = 5.456$, $p < .001$, however, not of REALISM, $F(1,253) = 0.273$, $p = .602$, and no interaction effect of FINGERS $\times$ REALISM, $F(5,253) = 1.240$, $p = .291$. Pairwise comparisons using Wilcoxon signed-rank tests revealed a significant difference between *all* and *missing index fingers* ($p = .048$). Others were above α-level .05. Mean scores and 95% confidence intervals of all conditions are shown in Figure 4.3a.

We additionally entered the demographic data GENDER, HANDEDNESS, EXPERIENCE IN PIANO PLAY, and PRIOR VR EXPERIENCE of the participants as additional between-subject factors for a mixed-model ANOVA. The factors showed neither significant main nor interaction effects (all with $p > .237$).

The results support the assumption that presence rather depended on which finger has been removed but not necessarily on avatar realism or the combination of both factors.

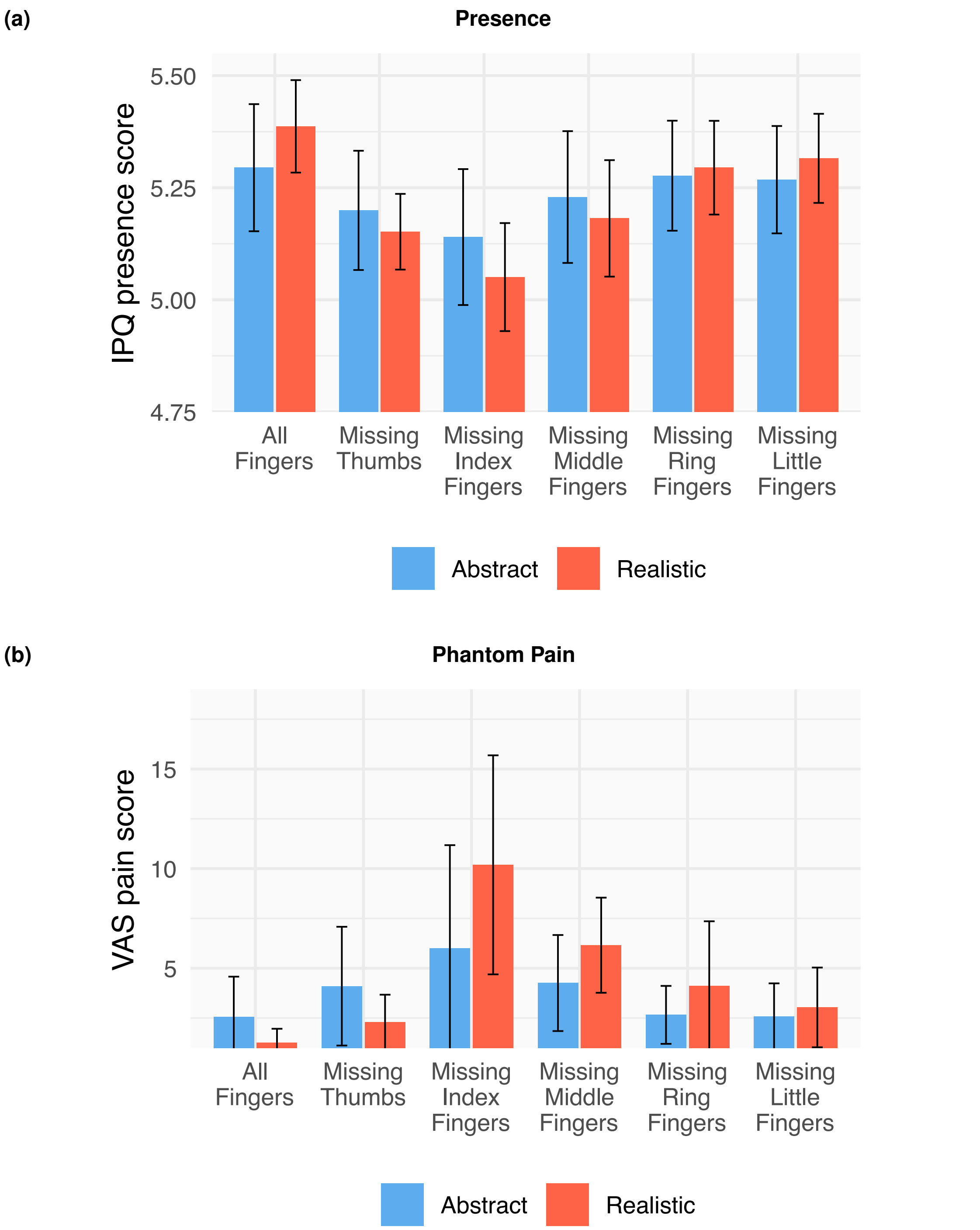

Figure 4.3: Average scores for the IPQ (a) and the VAS pain assessment (b) for each condition. Error bars show the 95% confidence interval.

4.3.2 Phantom Pain

Using a repeated-measures ANOVA we found significant main effects of FINGERS, $F(5,253) = 5.050$, $p < .001$, and REALISM, $F(1,253) = 15.224$, $p < .001$, and an interaction effect of FINGERS × REALISM, $F(5,253) = 5.652$, $p < .001$.

Cross-factor post-hoc comparisons using Wilcoxon signed-rank tests revealed interaction contrasts between *all fingers* and *missing index fingers* ($p = .032$), *missing index fingers* and *missing little fingers* ($p = .013$), *missing index fingers* and *missing ring fingers* ($p = .002$), *missing index fingers* and *missing thumbs* ($p = .002$), *missing middle fingers* and *missing ring fingers* ($p = .026$), and *missing middle fingers* and *missing thumbs* ($p = .025$). Other pairwise comparisons showed no significant interaction contrasts (all with $p > .137$). Mean VAS scores of perceived pain are shown in Figure 4.3b.

Demographic information about GENDER, HANDEDNESS, and PRIOR VR EXPERIENCE were analyzed as between-subject factors using a mixed-model ANOVA. We found no significant effects of GENDER (all main and interaction effects with $p > .624$), however, significant interactions effects of FINGERS × HANDEDNESS, $F(5,242) = 4.596$, $p = .001$, and REALISM × HANDEDNESS, $F(1,242) = 6.910$, $p = .009$. Pairwise cross-factor comparisons could not reveal between which conditions the effects occurred through HANDEDNESS (all with $p > .819$). We found significant interaction effects of FINGERS × PRIOR VR EXPERIENCE, $F(5,242) = 5.978$, $p < .001$, and REALISM × REALISM × PRIOR VR EXPERIENCE, $F(5,242) = 2.924$, $p = .014$. Pairwise cross-factor comparisons only showed that the ratings of VR users with no prior experiences in VR were significantly higher while using *missing middle fingers* in *abstract* style ($M = 5.73$, $SD = 6.54$) than of VR users with prior experience who used *all fingers* in *realistic* style ($M = 0.95$, $SD = 0.87$, $p = .017$), and while using *realistic missing middle fingers* ($M = 11.07$, $SD = 5.07$) in contrast to experienced VR users using *abstract missing little fingers* ($M = 2.72$, $SD = 2.19$, $p = .011$). No further main or interaction effects were found. Kendall rank correlation analysis including phantom pain and IPQ scores could not reveal a significant (negative) correlation estimate ($\tau = -.60$, $p = .136$).

Thus, the results not only support the assumption that visually removing virtual fingers affects pain perception but also that it depends on which fingers have been removed, and which style they had. Potential effects of other factors on pain perception are negligible, except if users had prior VR experiences. Their ratings of pain perception were lower compared to users with no prior VR experience.

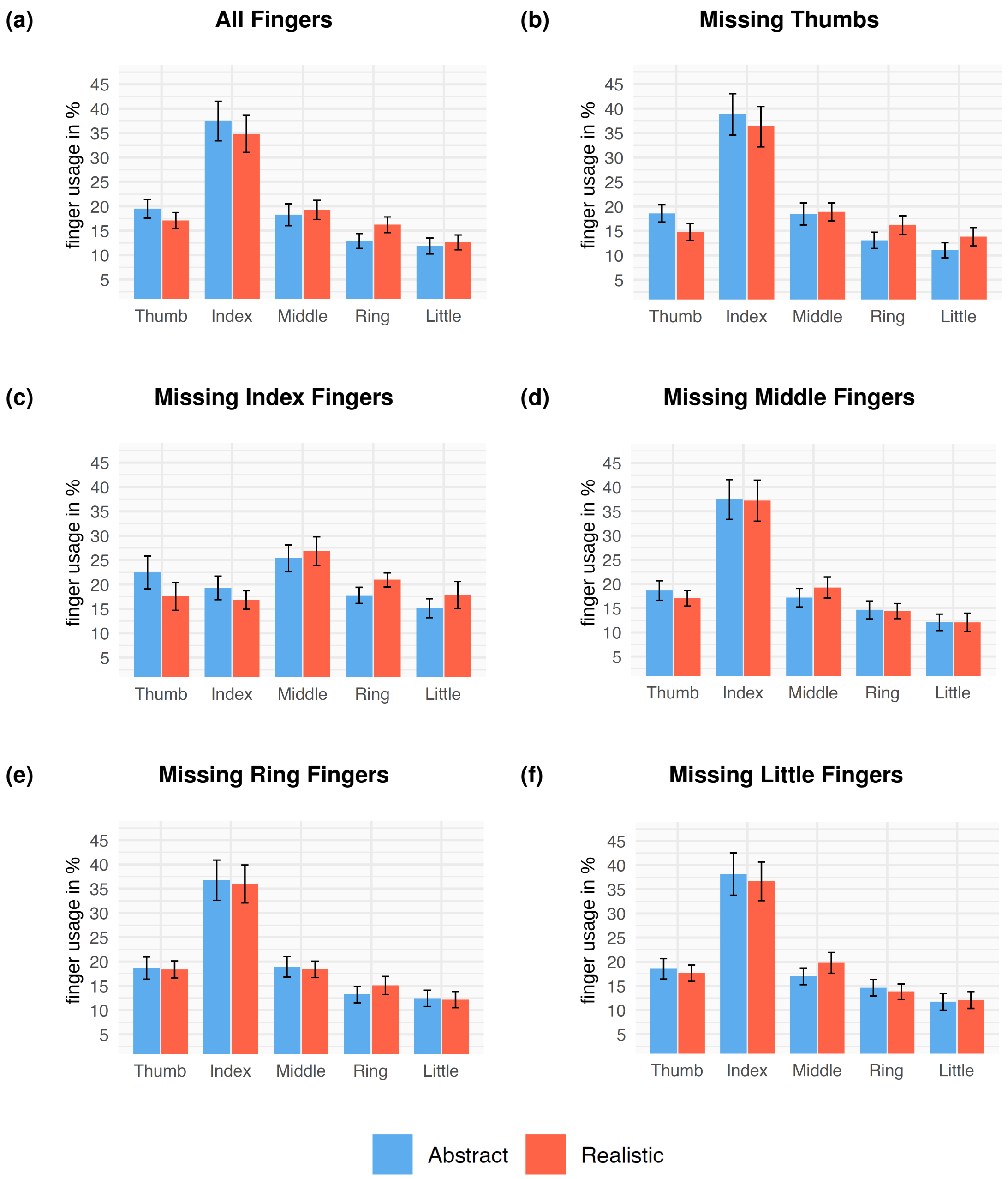

Figure 4.4: Average finger usage (in percent) for each condition. Removing the index fingers significantly increased the usage of the other fingers, which was not the case for the other ones. Thumb and index finger usage were higher with abstract hands than with realistic ones. Usage of middle, ring, and little finger was higher with abstract than with realistic hands. Error bars show the 95% confidence interval.

4.3.3 Finger Usage

Individual finger usage during the VR experience was determined through the number of virtual intersections between each fingertip (including the fingertips of the missing fingers) and the target objects (dice, keyboard, and user interface of the questionnaire). Since the fingers were removed on both hands, no distinction between left and right-handed participants was made in the analysis.

4.3.3.1 Individual Fingers Usage

Thumb usage showed no significant main effects of FINGERS, $F(5,253) = 1.245$, $p = .289$, however, of REALISM, $F(1,253) = 22.119$, $p < .001$, and a significant interaction effect of FINGERS × REALISM, $F(5,253) = 2.880$, $p = .015$. *Index fingers usage* showed significant main effects of FINGERS, $F(5,253) = 47.942$, $p < .001$, and of REALISM, $F(1,253) = 3.953$, $p = .048$. There was no interaction effect of FINGERS × REALISM, $F(5,253) = 0.295$, $p = .915$. *Middle fingers usage* showed significant main effects of FINGERS, $F(5,253) = 8.422$, $p < .001$, and of REALISM, $F(1,253) = 4.237$, $p = .041$. There was no interaction effect of FINGERS × REALISM, $F(5,253) = 0.295$, $p = .718$. *Ring fingers usage* showed significant main effects of FINGERS, $F(5,253) = 17.328$, $p < .001$, and REALISM, $F(1,253) = 17.747$, $p < .001$, and a significant interaction effect of FINGERS × REALISM, $F(5,253) = 3.039$, $p = .011$. *Little fingers usage* revealed significant main effects of FINGERS, $F(5,253) = 8.356$, $p < .001$, however, not of REALISM, $F(1,253) = 4.380$, $p > .05$, and no interaction effect of FINGERS × REALISM, $F(5,253) = 1.388$, $p = .229$. Means of finger usage between all tasks and participants (in percent) during the 12 conditions are shown in Figure 4.4.

Pairwise cross-factor comparisons of the *thumb usage* showed that their activity significantly differed between *missing index* and *missing ring fingers* ($p = .029$). All pairwise post-hoc comparisons of finger usage while experiencing *missing index*, *middle*, *ring*, and *little fingers* only revealed significant differences between the *index fingers usage* as well as the other conditions: *all fingers usage* (all with $p < .001$), *thumbs usage* (all with $p < .001$), *middle fingers usage* (all with $p < .001$), *ring fingers usage* (all with $p < .001$), and *little fingers usage* (all with $p < .001$). Differences among the other fingers' usage were not significant.

The results showed that hands with missing index fingers increased the usage of the other fingers and decreased the relative activity of the index finger. Furthermore, the

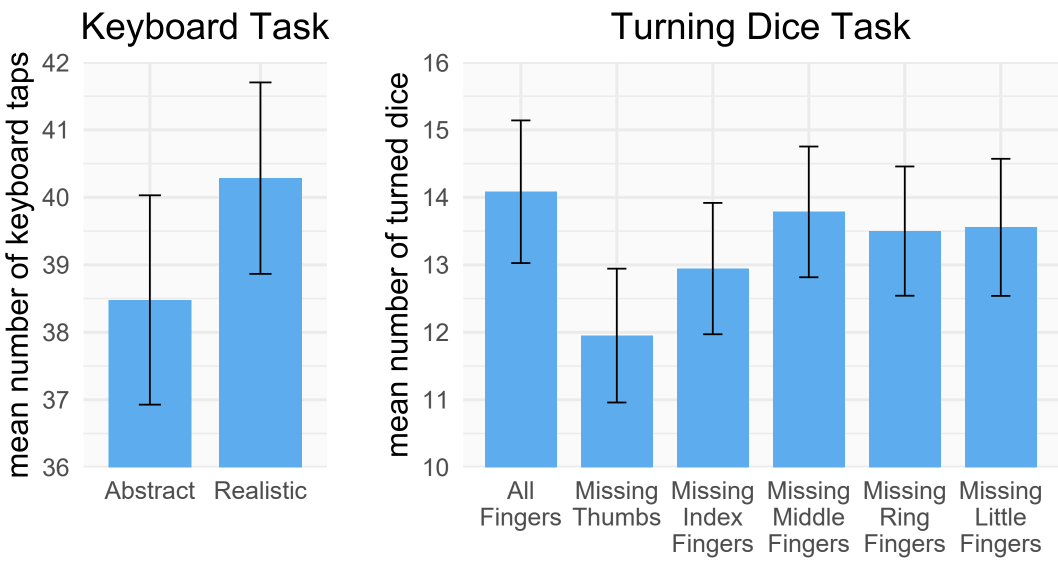

Figure 4.5: Main effects of realism (no effect of missing fingers) on the mean number of correct taps in the keyboard task (left); main effects of missing fingers (no effect of realism) on the mean number of turned dice triples in the turning dice task (right).

style of the avatar hands had a significant effect on finger usage among all hands. Both, thumb as well as index finger usage of abstract hands were higher than with realistic ones—even when they were missing. This relation was generally inverted considering the middle, ring, and little finger, whose usage with realistic hands was higher than with abstract ones.

4.3.3.2 Piano Play Experience in Keyboard Task

Ten participants (41.6%) stated that they learned piano play with 10 fingers. In order to understand if removing fingers and changing the realism of their avatar had potential effects on highly trained finger behavior during a piano play task, we entered the finger usage during the keyboard task into a three-way ANOVA with FINGERS and REALISM as independent variables, and EXPERIENCE IN PIANO PLAY as between-subject variable. For the sake of clarity, we only report the interaction effects with EXPERIENCE IN PIANO PLAY. Means of thumb and index finger usage during the keyboard task and participants with and without experience in piano play are shown in Figure 4.4.

We found a significant three-way interaction of FINGERS × REALISM × EXPERIENCE IN PIANO PLAY, $F(5,242) = 2.559$, $p = .028$, on finger usage while pressing keys with the virtual piano using a *missing thumb*. Pairwise cross-factor post-hoc comparisons revealed significant differences between the usages of *index* and *middle finger* ($p = .028$), and *index* and *little finger* ($p = .047$). There was a significant two-way interaction of FINGERS × EXPERIENCE IN PIANO PLAY, $F(5,242) = 3.274$, $p = .007$, on *index finger* usage. Pairwise post-hoc comparisons revealed significant differences between the usages of *all* and *index finger* ($p = .032$), *index* and *middle finger* ($p = .010$), and *index* and *thumb* ($p = .026$). Further significant interactions with EXPERIENCE IN PIANO PLAY and the other factors were not found.

Mean comparisons of the keyboard task confirmed that thumb and index finger usage of abstract hands were generally higher than with realistic hands, however, experienced piano players using a missing index finger rather tended to use their thumb instead of the other fingers (such as the middle finger) when the hands were realistic.

4.3.3.3 Task Performance

Finger usage obviously depends on the task (finger usage showed significant two-way and three-way interactions, all with $p \leq .001$), even when the participants in our experiment were allowed to interact with all fingers. As expected, means of finger usages (not reported) indicate a higher activity of the index fingers during the keyboard task and a synchronized finger usage while turning dice. As finger usage depends on the task, we investigated the participants' behavior through analyzing the task performance of both tasks. Thus, we determined the mean number of correct performed taps during the keyboard task and the mean number of correct placed dice triples during the turning dice task for each participant (see Figure 4.5).

There was no significant main effect of FINGERS, $F(5,253) = 0.701$, $p = .623$, however, of REALISM, $F(1,253) = 5.703$, $p = .018$, and no interaction effect of FINGERS × REALISM, $F(5,253) = 1.863$, $p = .101$, on the number of (correct) taps in the keyboard task. A main effect of REALISM was also found when considering five-fingered hands only, $F(1,23) = 4.563$, $p = .044$. Entering EXPERIENCE IN PIANO PLAY, HANDEDNESS, or PRIOR VR EXPERIENCE as between-subject variables into the analysis revealed no further main or interaction effects (all $p > .332$).

There was a significant main effect of FINGERS, $F(5,253) = 2.528$, $p = .030$, however, not of REALISM, $F(1,253) = 0.093$, $p = .761$, and no interaction effect of FIN-

GERS × REALISM, $F(5,253) = 1.065$, $p = .381$, on the number of (correctly) turned dice triples in the turning dice task. Pairwise post-hoc comparisons showed a significant difference between *all fingers* and *missing thumbs* ($p = .029$). Means of correct keyboard taps using the *abstract* and *realistic* hands during the keyboard task and of the correctly turned dice triples using the different hands during the turning dice task are shown in Figure 4.5. No main or interaction effects of EXPERIENCE IN PIANO PLAY, HANDEDNESS, or PRIOR VR EXPERIENCE were found (all $p > .103$).

4.4 Discussion

In this study, we investigated the effects of missing fingers and hand realism of avatars on presence, phantom pain perception, and finger usage in VR. Previous work already showed that presence decreased the more fingers of a realistic virtual hand were being removed (Schwind et al., 2017a). In this work, we showed that this not only depends on realism but also on the individual fingers. Lowest presence scores and highest phantom pain scores were measured using a missing index finger. We observed that presence did not significantly decrease using an abstract avatar and that the reduction of only one finger was not sufficient to show that presence depends on both factors: missing fingers and realism. This is still in line with results of Schwind et al. (2017a), who found similar results when removing little fingers. A visual comparison of the means in our study indicates that high levels of presence in VR can be maintained when fingers are being firstly removed from the outer hand side.

Our findings confirm that virtual limb loss causes phantom pain (Schwind et al., 2017a). In our study, we used the VAS measure for quantifying the subjective intensity of perceiving phantom pain through the virtual illusion of having no limb. Even when the participants did not experience any physical harm, virtual finger removal could induce sensations of phantom pain. While these sensations can be explained by a fear of losing the own limbs, phantom pain sensation depends on the individual finger and the realism of the avatar. Highest pain perception was perceived using a missing index finger, however, significantly increased when the avatar was realistic. Interestingly, the loss of the thumbs was not perceived that bad as one can assume through its importance in everyday life. This could be potentially caused by the tasks used in our study where the thumbs were turned away from the viewer and hidden by the rest of the hand. In addition, abstract hands with all fingers or missing thumbs received slightly higher pain perception ratings than with realistic hands, which was not the case for the other fingers. It is possible that the thumbs might be considered differently from a functional aesthetic view, which could also be related to the number of bones as thumbs have potentially fewer missing sub limbs than the other fingers.

An important aspect to be reconsidered at this point is the negative impact of phantom pain on presence. As previously mentioned, related work suggests that increased phantom pain decreases presence (Schwind et al., 2017a). Independently from our finding that no (negative) correlation has been found between phantom pain perception and presence, we assume that a relation of both constructs should not be assumed per se. The original assumption was that the mismatch between virtual and physical appearance is responsible for decreasing presence using altered body structures. However, if presence is defined as the extent to which one can ignore a mediating technology (Lombard & Ditton, 1997), then increased phantom pain using an altered body structure rather indicates that VR users cannot ignore and *accept* the virtual illusion—even when the body structure does not match. In this case, phantom pain, not presence, is a measure for accepting the VR experience and the illusion of integrating a virtual body into the own body schema, which was not the case if we only consider scores of presence. As presence questionnaires were developed when tracking technologies in VR were mainly used to compute the translation of the head for stereoscopic viewing using HMDs, we argue that future questionnaires measuring presence must actually inherently differentiate between *being and acting in a virtual world* and *being and acting within a virtual body*. A reliable and objective measure of presence must contribute to an understanding of this relationship.

The behavioral analyses of the participants' finger usage can help to further objectify the integration of avatars into one's own body. As expected, the participants' finger usage showed that they significantly reduced the interaction of the missing index fingers and increased the usage of the other ones when they perceived the illusion of virtual hands without index fingers. However, we found that relative usages of thumb, as well as index fingers, were higher while using abstract hands than with realistic ones. The relative usage of the other fingers increased or decreased contrarily. As all hands had the same skeleton and were precisely matched to that, participants' ability to correct pose errors or be affected by tracking errors was practically ruled out. This is supported by the finding, that the effect occurred even in fingers that were missing. We assume that human cognition integrates dominant limbs (Raj & Marquis, 1999) or limbs with the highest functional motor control (thumb and index fingers; Aoki & Shinohara, 2009) firstly into the body schema when the virtual appearance does not resemble the own body. This confirms findings of optimal cue combination and research investigating the trade-off between haptic and vision while combining cues into a unified percept, whereas haptic stimuli are more likely to be integrated into the body schema when the visual perception ignores non-informative stimuli (Ernst & Banks, 2002; Botvinick & Cohen, 1998; Schwind et al., 2018a).

Inexperienced participants during the piano play used their thumbs instead of the other fingers when their index fingers were missing, which indicates that dominant limbs try to swap their roles among each other first when the player is not trained in using the other fingers. As this was not the case for experienced participants during the piano play, we assume that finger substitution, a playing technique used to facilitate passage between two keys, makes it easier for trained players to bring two fingers together when the index fingers are missing. A realistic appearance further helps them to perform this technique but could not increase the task performance of trained participants. In addition, we found a decreasing performance during the dice task attributed to participants who ignored the missing thumbs, which prevented them to grab or lift the cubes correctly.

Due to the dominance of vision, finger usage changed the task performance indices of one of the most natural interactions—grasping objects. While the removal of thumbs could be compensated through the usage of other fingers, a comparison of the means indicates that the index fingers play also an important role while performing the grasping gesture, which is supported by the usage measures only. To understand to which extent the fingers affected the performance in our tasks, nonlinear regression was conducted. As we found that the thumbs and index fingers have the highest impact on task performance, we conclude that they should not be removed when providing hand avatars with missing fingers. Removing multiple fingers at the same time could further help to understand if the herein found effects behave additively and lead to a linear outcome if more fingers have been removed (e.g., a linear decrease of presence; Schwind et al., 2017a). Source code, data, and assets to replicate our experiment are available on github[1].

[1] `https://github.com/valentin-schwind/lessfingers-usage`

4.5 Limitations and Future Work

Our study showed effects after one minute of task completion time (TCT), however, long-term or habituation effects have not been observed and should be investigated by future research. Moreover, the herein presented results are task-specific. More research is required to learn more about the generalization of the results. As we removed each of the five fingers of both hands individually, we recommend investigating how the removal of more finger combinations and asymmetric finger removal between the left and the right hand affect interaction and subjective responses. Integration of dominant hands and further limbs were not investigated in detail and could help to further understand the integration of dominant body parts depending on their realism. Particularly handedness and the integration of dominant fingers using avatar hands with different degrees of realism could be further investigated by future work.

Interaction effects of avatar realism, handedness, and experience in piano play potentially support the assumption of the integration of dominant limbs, however, could not further be investigated as only one of the participants experienced in piano play was left-handed. To further investigate that assumption using the herein presented task, a balanced sample of left- and right-handed piano players is required or an experimental design fully ruling out that participants can benefit from previous experiences and training. Based on findings of previous work and learning effects of the participants (Knierim et al., 2018; Feit et al., 2016), we do not recommend typical typing tasks as an alternative, but probably a typing task with a random keyboard layout. Our findings also refer to human-like body structures only. The integration of body structures of other species or body extensions has not been studied in this context and could also be the subject of further investigations.

4.6 Implications

For developers and designers of immersive VR applications, who want to alter the users' body structure by reducing the number of fingers, we recommend considering realism as our measures using realistic hands showed an increased phantom pain perception. These results indicate that there is a strong bond between the users and their virtual hands that can be utilized by designers to induce various effects to enhance the VR experience. Shocking moments in VR horror games, for example, could be reinforced through altered body structures with a realistic appearance. Habituation effects can be assumed as users with prior VR experience perceived significantly less phantom pain. Basically, designers have to consider that the deviation of the virtual body structure from the user's real body can cause undesired behavioral and perceptual changes. Hence, we recommend that fingers (particularly index fingers and thumbs) should not be removed when the interaction with virtual objects or interfaces should not be significantly affected. As shown in our study, the sense of presence and the performance of absolutely natural and intuitive interactions like grasping objects could be negatively influenced by altered body structures.

We argue that the behavioral effects caused by the visual appearance of the virtual hands cannot be definitely attributed to the Proteus effect, as there is no stereotype connected with abstract hands and hands with missing fingers. However, as our results show that users adapted their behavior based on the visual appearance of the virtual hands, it is important to consider that the design and appearance of our avatar hands could influence the way users interacted in VR. Since we negatively affected the performance and VR experience using avatars with altered body structures, we, therefore, need to find out how to systematically induce behavioral changes for improving performance in VR.

5

Improving Physical Performance

Research found that the embodiment of avatars with certain characteristics can affect users' behavior and experience during interaction in VR. In two studies, we show how the embodiment of avatars with a muscular and athletic appearance can improve performance during physical exercise in VR. We found that muscular avatars can decrease the perception of effort and increase the grip strength. We also found that athletic avatars can reduce physiological responses to exertion. Our work demonstrates that "high-performing" avatars can positively affect the user during physical exertion in VR.

This chapter is based on the following publications:

Kocur, M., Kloss, M., Schwind, V., Wolff, C., & Henze, N. (2020c). "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*. New York, NY, USA: Association for Computing Machinery, pp. 193–205. ISBN: 9781450380744. DOI: 10.1145/3410404.3414261.

Kocur, M., Habler, F., Schwind, V., Woźniak, P. W., Wolff, C., & Henze, N. (2021b). "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*. CHI '21. Yokohama, Japan: Association for Computing Machinery, pp. 1–18. ISBN: 9781450380966. DOI: 10.1145/3411764.3445160.

5.1 Body Ownership of Muscular and Athletic Avatars

In previous chapters, we learned about the core concepts of BOIs and how we can induce a feeling of ownership of virtual avatars. When applying visuo-tactile synchrony, users experienced a virtual hand with a rubber appearance as if it was their own hand. As asynchronous stimulation significantly decreased the extent of the RHI, it is necessary to apply temporally and spatially synchronous stimulation to induce an ownership illusion of virtual hands. To elicit ownership of virtual hands with visual characteristics that strongly deviate from the users' physical hands, we used visuo-motor synchrony by tracking the users' movements and transferring them onto the animation of the avatar. As a consequence, users interacted with virtual hands by moving their physical hands and fingers. We found that altered body structures in terms of removed fingers created phantom pain sensations and reduced the sense of presence. Furthermore, our results indicate that users adapted their behavior and interaction in VR based on the visual appearance of the avatars. The way they used their fingers was affected by the design of the virtual hands.

In this chapter, we integrate this gained knowledge into the design process of avatars to make users embody full-body avatars with a muscular and athletic appearance to improve physical performance in VR. We used realistic humanoid avatars, as we learned in the previous chapter that altered body structures can cause negative behavioral and emotional responses that are even higher at high levels of realism. We induced illusory ownership of avatars with characteristics that differ from the users' attributes using visuo-motor synchrony via full-body motion capture. By using virtual mirrors, users could constantly perceive their virtual body moving synchronously with the motion of their real body parts. Hence, we could investigate whether the embodiment of avatars with a muscular and athletic appearance can increase users' performance in physical tasks in VR. We also explored how athletic avatars affect the HR response during exertion. To understand the impact of different avatars on the VR experience, we analyzed the body ownership, the sense of presence, and the user identification. Effects would have consequences and implications for the design of health-related VR systems, as the avatar could be utilized to engage users during physical exertion, promote physical activity, and, consequently, result in enhanced exercise benefits. Hence, findings of this research can be helpful for designers and developers of VR applications to create more effective avatars that positively affect users' exertional responses.

5.2 Avatars’ Effects on Physical Performance

In a meta-analysis, Ratan et al. (2019) concluded that the Proteus effect is a valid phenomenon with consistent effect sizes between small and medium. However, there is still little known about the effect on users’ physical performance and responses to physical activity in VEs.

Lin et al. (2021) reported that avatars with pronounced abdominal muscles affected users’ exercise behavior. Users embodying avatars with a “six-pack” were less physically active than those with a “normal” avatar. The authors argued that users perceived themselves as not needing to exercise that much while embodying the avatar with a muscular abdomen as the avatar is already in a good shape. Similar results were shown in another study where the authors manipulated the age of the avatars instead of their abdominal muscles (Lin & Wu, 2021). This study showed that the embodiment of approximately 20 years younger avatars increased the perception of effort during exercise. In this vein, Czub and Janeta (2021) compared a VR condition where participants performed biceps curls while embodying an athletic avatar with a non-VR condition. The authors found that participants performed more repetitions in the VE. These findings are in line with Matsangidou et al. (2019), who reported that participants’ perceived pain was lower during biceps curls in VR compared to the real world. As in both studies the control condition was outside of VR without an avatar, it remains unclear whether such effects can be attributed to the avatar and its visual characteristics.

In a further study, Peña and Kim (2014) found that players of a competitive virtual tennis game were physically more active when playing with a normal avatar compared to an avatar with an appearance the authors dubbed “obese”. They replicated these findings in a second study and identified the body composition of the opponent’s avatar as a significant moderator (Peña et al., 2016). The authors introduced the “take it easy” hypothesis—players are less physically active when they think they have an advantage over the opponent—and the “give up” hypothesis—players exercise less when their appearance indicates to have a disadvantage compared to the opponent (Peña & Kim, 2014). This is in line with Keenaghan et al. (2020), who found that cycling against an idealized version of oneself can have a negative impact on the physical performance due to self-discrepancy. Nonetheless, they also revealed that racing against avatars, which depicted a realistic enhancement compared to an unrealistic idealized version, could positively affect the users’ achieved power output on an exercycle. Since these studies investigated the effects of avatars in VEs with multiple characters, their reciprocal impact has to be considered. Consequently, further psychological effects such as behavioral confirmation (Snyder et al., 1977; Yee, 2007), deindividuation (Yee, 2007), or competition (Murayama & Elliot, 2012) can occur and, therefore, moderate avatars' effects on users. Hence, it remains unclear whether and how avatars affect the embodied user's performance in physical tasks when being alone in VR.

5.3 Study I: Muscular Appearance

One main characteristic of behavioral changes is exerting forces through the proprioceptive system. In this section, we investigate whether the visual appearance of an avatar can be altered in a way that users will perform better in physical tasks when their virtual appearance indicates to be physically stronger. Furthermore, effects on weight perception, the self-perceived fitness (SPF), the sense of presence as well as body ownership are assessed.

5.3.1 Study Design

To investigate the effect of avatars' muscular appearance on users' physical performance and their perception of effort, we used a mixed design with the between-subjects variable GENDER and the within-subjects variable BODY with the three levels *non-muscular*, *medium*, and *muscular*. Thus, participants embodied avatars of their own gender with different muscular appearance. To reduce order effects we counterbalanced the avatars using a 3×3 Latin Square.

5.3.2 Stimuli

We used three male and three female avatars with different muscular appearance (see Figure 5.1). We designed the avatars using the 3D-suite Daz3D[1]. We used the characters Genesis 8[2] Male and Female, and adapted their muscular appearance by morph targets for Male[3] and Female[4]. For the male and female avatars, we defined the standard Genesis 8 Male and Female avatar as our stimuli with medium muscularity. We estimated the

[1]https://www.daz3d.com/
[2]https://www.daz3d.com/genesis8
[3]https://www.daz3d.com/massive-morphs-for-genesis-8-male
[4]https://www.daz3d.com/massive-morphs-for-genesis-8-female-s

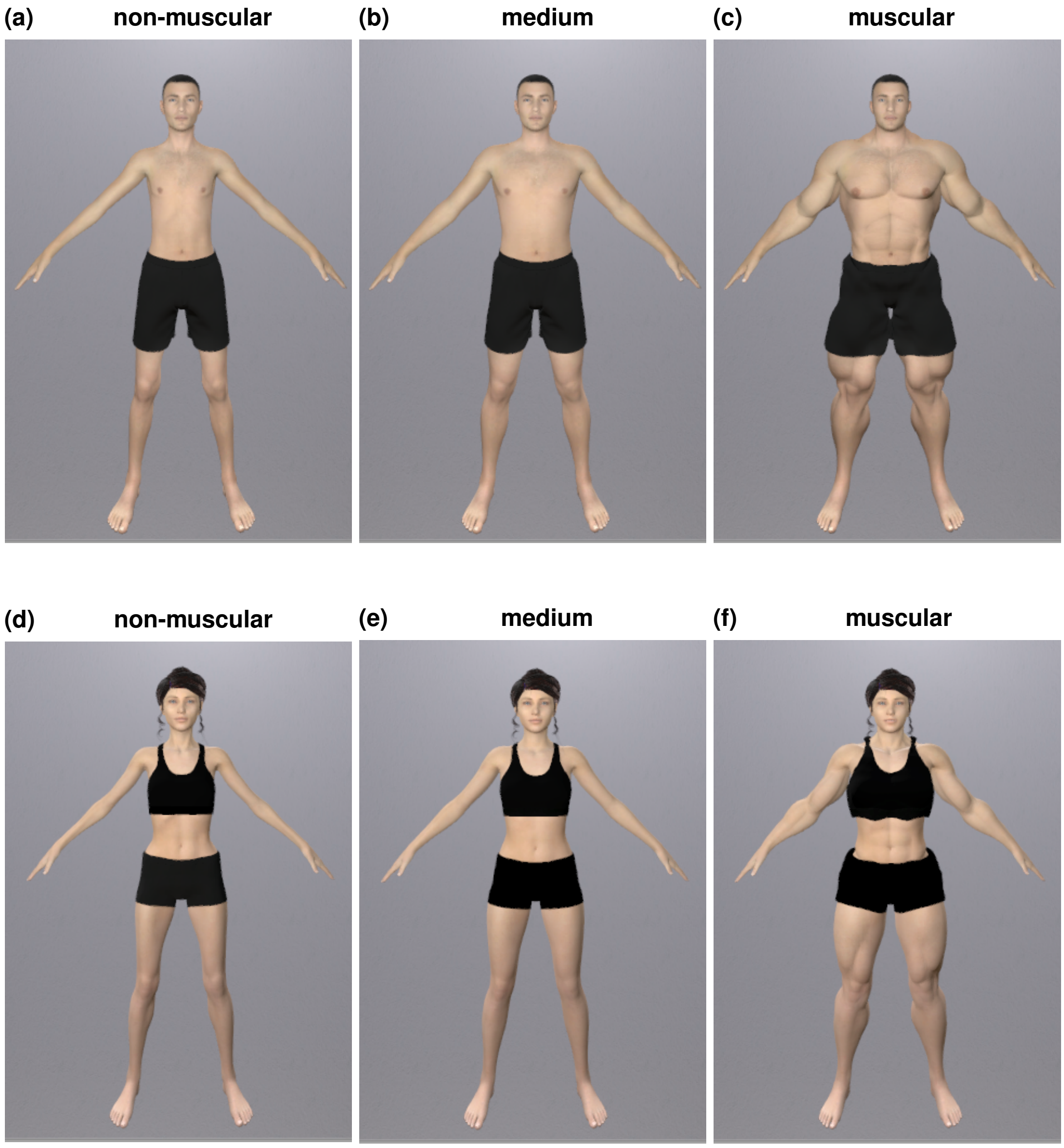

Figure 5.1: 3D models of the avatars with different muscular appearance. The three avatars at the top (a - c) were embodied by male participants, whereas the three avatars at the bottom (d - f) were embodied by female participants. The avatars have a non-muscular, medium, and muscular body.

Figure 5.2: Participants in the virtual world from a first-person perspective during the tasks while looking in the mirror (top), and the corresponding real world (bottom). Participants performed three tasks: the JND task, the grip strength task, and the isometric force task with shoulder abduction (from left to right).

avatars' body weight based on the formula by Buckley et al. (2012): According to the medium avatars' body measurements, an adult male would weigh 72 kg and an adult female would weigh 64 kg. Based on the measurements of the medium avatars, we increased the avatars' proportions using morph targets by approximately 34% muscle mass to obtain the muscular avatar, and decreased approximately 17% of muscle mass to create the non-muscular avatars with a constant body height. Each avatar model had the same skeleton with an identical configuration of bones. We used the game engine Unity3D (v. 2018.3.2f1) to implement the VR application. We designed a virtual scene consisting of a room with light walls, a table, a mirror with stereoscopic reflections, and a dumbbell stand.

5.3.3 Measures

We took several measures to determine the effects of the independent variable. We measured the perceived exertion during an isometric force task using the established Rating of Perceived Exertion (RPE) scale (Borg, 1982). We assessed the grip strength using a dynamometer as a force measuring device. We also measured the just-noticeable difference (JND) using a psychophysical test with a constant stimulus and five comparison stimuli in a two-alternative forced-choice (2AFC) task. Furthermore, participants were asked to fill in a self-appraisal questionnaire to determine the SPF (Delignières et al., 1994). Additionally, we quantified the sense of presence with the single item G1 of the IPQ (Schubert et al., 2001), and assessed the body ownership illusion with the Body Representation Questionnaire (BRQ; Banakou et al., 2013; Banakou et al., 2018) after each condition. In line with Schwind et al. (2019), all questionnaires were filled in the VR environment. Since we assumed that the task to assess the grip strength and the isometric force task to quantify the perceived exertion could affect the sensitivity to weight discrimination, we decided for a constant order of tasks in each condition and started with the psychophysical test to determine the JND, measured the grip strength afterward, and finally assessed the perceived exertion.

5.3.3.1 Perceived Exertion

We investigated the perceived exertion during a force task with isometric muscle contractions. According to a standardized procedure (Andersen et al., 2010; Hughes et al., 1999; Myers et al., 2015), participants held one weight of 1 kg in each hand for 60 seconds in a position at 90 degrees of shoulder abduction in the scapular plane (see Figure 5.2). Originally defined as “the feeling of how heavy, strenuous and laborious exercise is” (Borg, 1962), we determined the perceived exertion during a physical exercise based on a popular and well-established experimental procedure (Borg, 1962; Borg, 1982; Borg, 1990). We presented a virtual scale—the psychophysical Borg’s RPE scale (Borg, 1982)—throughout the isometric force task. The RPE scale was designed to increase linearly with physical exercise intensity and consists of 15 grades from 6 to 20. Every second grade is combined with a textual representation of the intensity, e.g., “7” stands for “very, very light” and “19” for “very, very hard” (Borg, 1982). An approximate estimation of the current HR can be calculated by multiplying each grade by 10, e.g., an intensity of 11 approximately matches a HR of 110. In the last five seconds of the task, the participants indicated their perceived exertion by orally communicating the grade that best represented their current perception of effort.

5.3.3.2 Grip Strength

As grip strength correlates with the overall muscle strength of a person (Tietjen-Smith et al., 2006; Wind et al., 2010), we used grip strength as a dependent variable. Based on a standardized approach proposed by Roberts et al. (2011) and the American Society of Hand Therapists (Fess, 1992), we created a task to assess participants' grip strength using a dynamometer for force measurement. In a standing position, participants adducted and neutrally rotated the shoulder of the dominant hand holding the dynamometer with the elbow flexed at 90 degrees (see Figure 5.2). The non-dominant arm was in a neutral, dangled position. Participants were not aware of the outcome of the measurements.

5.3.3.3 Body Ownership

To quantify the induced body ownership, we used the BRQ (Banakou et al., 2013; Banakou et al., 2018) with the single-item subscales vrbody ("I felt that the virtual body I saw when looking down at myself was my own body"), mirror ("I felt that the virtual body I saw when looking at myself in the mirror was my own body"), features ("I felt that the virtual body resembled my own real body in terms of shape, skin tone or other visual features"), twobodies ("I felt as if I had two bodies"), and agency ("I felt that the movements of the virtual body were caused by my own movements").

5.3.3.4 Self-Perceived Fitness

We investigated the effect of different muscularity of avatars on the SPF using a version of the self-appraisal questionnaire by Borg et al. (1972) adapted by Delignières et al. (1994). The authors created a questionnaire with the five dimensions endurance, strength, flexibility, body composition, and fitness rated on a 13-point scale with an ascending level from 1 to 13 (Delignières et al., 1994). Every second point consists of additional verbal expressions.

5.3.3.5 Just-Noticeable Difference

The JND is a psychophysical measure that stands for the amount of a change in a stimulus to be detectable and noticeable (Wozniak, 1999). Also referred to as the difference threshold, we implicitly identified the JND in a 2AFC task for weight perception to investigate the sensitivity to weight. We applied the method of constant stimuli (Knoblauch & Maloney, 2012; Gescheider, 1997) based on the procedure by Wallace et al. (2002), in which the participants estimated weight pairs where one always had a constant weight. The constant weight was 200 g whereas the comparison weights were 205 g, 210 g, 215 g, 220 g, and 225 g. The participants were presented the constant weight and a comparison weight in a randomized order. On each trial, the participants lifted the two weights in succession and held them for three seconds with their left hands, as the left side of the human body is more sensitive to the perception of changes in weights (Murray et al., 1999).

After lifting and putting down the second weight, they immediately had to decide which of the two weights appeared to be heavier. After each response, a new weight pair was presented randomly. In total, each weight pair was compared six times in a randomized order so that three times the constant weight and three times the comparison weight was presented first. This procedure resulted in 30 weight comparisons. Based on Schwind et al. (2018a), who found an effect of limb ownership on the JND, we hypothesize that the JND while embodying a muscular or non-muscular avatar differs from the JND while embodying a medium avatar. We assume that the variation of the degree of the body ownership due to the muscular appearance of avatars changes the user's weight perception.

5.3.4 Apparatus

We defined an area (width: 4.2 m, length: 3.9 m) in our VR laboratory where participants could move during VR exposure. We induced the BOI by substituting the participant's real body through a non-muscular, medium, and muscular avatar in VR using an HTC Vive HMD with an HTC wireless adapter to allow participants to move freely within the VR area. The integrated Vive chaperone system rendered virtual lines when users approached the space boundaries preventing them to go beyond the defined VR area. The HMD has a wide horizontal field of view of 100° and a spatial resolution of 1080×1200

pixels per eye displayed at 90 FPS. Participants perceived the virtual body and the surrounding environment from a first-person perspective. Through a virtual mirror, the participants could constantly perceive their virtual body as their own.

We enhanced body ownership and agency through visuo-motor synchrony. Participants' real movements were captured with OptiTrack motion capturing[1] (Natural Point Inc., Corvallis, USA) and transferred onto the virtual skeleton of the avatar. To track participants' full-body motion, we employed a marker-based OptiTrack motion tracking system with twelve cameras (eight PRIME 13 and four PRIME 13W) and the software Motive (v. 2.1). The motion tracking software ran on a dedicated PC with Windows 10, Intel i7-8700, 26GB RAM, and an NVIDIA GeForce GTX 1080 graphics card. We calibrated the OptiTrack system according to the manufacturer's specification and achieved an exceptionally precise calibration result (overall reprojection mean 3D error: 0.852 mm, triangulation residual mean error: 0.8 mm, overall wand mean error: 0.187 mm, worst camera mean 3D error: 0.949 mm).

Participants had to wear black marker suits (OptiTrack Motion Capture Suit Classic[2]) available in different sizes (S, M, and L) with 39 passive markers. Furthermore, they had to wear a pair of black gloves (100% cotton) with 16 active markers resulting in a total of 55 optical markers attached in a given pattern using velcro. To ensure accurate tracking of each individual finger, we used an active marker set (OptiTrack active tag[3]) that consisted of eight through-hole LEDs emitting a wide-angle IR pulse. They were attached to the gloves by sewing each LED with eight to 10 stitches onto each fingertip. The OptiTrack system tracked participants' skeleton with 240 FPS and was synchronized with the HMD's head tracking to avoid interference. Using UDP multicast the skeletons were streamed through a local 1000 Mbit network connection via the NatNet protocol to the PC (Windows 10, Intel i7-8750H, 16GB RAM, NVIDIA GeForce GTX 1060 graphics card) that ran the VR application and rendered the 3D scene.

To create eight physical weights, we used fine-grained sand to fill ordinary beverage bottles made of plastic with screwcaps. We used six weights of 200 g, 205 g, 210 g, 215 g, 220 g, and 225 g for the JND task. Additionally, we used two weights of 1 kg for the isometric strength task. We modeled black virtual replicas of these weights each with a grey stripe in the center indicating the area participants should grip the

[1] `https://optitrack.com/`
[2] `https://optitrack.com/products/motion-capture-suits/`
[3] `https://optitrack.com/products/active-components/`

	Female ($N = 15$)		Male ($N = 15$)	
Scales of the SPF Questionnaire (Min = 1, Max = 13)	*M*	*SD*	*M*	*SD*
Fitness	4.86	2.50	5.00	2.00
Strength	6.46	1.68	5.93	2.68
Body Composition	6.86	2.03	6.53	2.44
Endurance	6.26	2.01	4.20	2.70
Flexibility	6.33	2.69	5.53	2.26

Table 5.1: Means (M) and standard deviations (SD) of the subscales of the SPF questionnaire by Delignières et al. (1994).

weight. The physical weights were tracked using a rigid body and were rendered in VR according to their real position. For the JND task, we used a table adjustable in height to ensure that each participant lifted the weights in succession in an identical lifting motion from the same position relative to their body height. In VR, a virtual table was placed in a fixed position in the virtual scene. To measure grip strength we used a handheld dynamometer (Camry Digital Hand Dynamometer Grip Strength EH101–37, Camry Electronic, Zhongshan, China) with a digital display and an adjustable grip. We constructed an equivalent 3D model of the dynamometer with the 3D creation software Blender (v. 2.79). To avoid tracking errors due to the occlusion of the active hand markers by the dynamometer, we did not track the dynamometer with a rigid body but integrated the 3D model into the skeleton of the avatars.

5.3.5 Participants

We recruited 30 participants (15 female, 15 male) via a mailing list of our institution. Their age ranged from 19 to 36 ($M = 22.13$, $SD = 3.78$). To assess the participants' level of fitness, we used the SPF questionnaire by Delignières et al. (1994) as part of the demographics (see Table 5.1). All participants were compensated with one credit point for their study course. All of them had a technical background in computer science or engineering. One participant was left-handed. None of the participants reported any pain in the upper limbs before and after the study. This study received ethics clearance according to the ethics and privacy regulations of our institution and, thus, follow the policies of our country and funding body.

5.3.6 Procedure

Before entering the VE, participants signed an informed consent form and filled in a demographic questionnaire. As part of the demographics, we assessed the participants' level of fitness. Afterward, we provided a brief introduction into VR and the participants could get familiar with our VR system. We highlighted that the participants could withdraw or discontinue participation at any time without penalty or losing their compensation. After a short warm-up including repeated shoulder abductions and adductions, we then supported the participants to put on the body tracking suit, the HMD, and the pair of gloves, which were already attached with optical markers. Before starting the scene, we adjusted the HMD to the participant's head and calibrated the interpupillary distance to ensure the best visual results. We adjusted the dynamometer grip to the participant's hand size based on a standardized procedure (Firrell & Crain, 1996). The physical table was adjusted to the participants' body height so that they could lay down the arms on the table in 90 degrees elbow flexion.

After entering the scene, the participants had a one-minute exposition period to get accustomed to the avatar where they were instructed to stand in front of the mirror and perceive the virtual body while moving the limbs. After this, they were asked to perform the JND task by standing in front of the virtual table laying down the left arm onto the table in 90 degrees elbow flexion. The investigator placed each physical weight in a fixed position on the table right in front of the left arm of the participant. This was the starting position the participants lifted the weights from. The corresponding virtual weight was spawned when the real weight collided with a virtual trigger box surrounding the starting position. The participants lifted the weights to a predefined height indicated by a virtual blue bar. As soon as the virtual weight collided with the bar, the bar became red and turned blue again after three seconds. This indicated that the participant had to put down the weight back to the starting position. In a randomized order, the investigator replaced each weight one after another. After each weight pair, a virtual text appeared on the table in front of the participant with the following question: "Which one was heavier?". The participants had to guess by tapping one of two virtual buttons with a "1" indicating that the first presented weight was heavier, and a "2" that the second weight was perceived as heavier. After virtually pressing one of the two buttons, the next trial started by presenting a new pair of weights.

After the JND task, the investigator paused the VR application and the screen faded to black. The investigator handed over the dynamometer and restarted the VR application with a scene where the participants embodied the same avatar as before in the corresponding experimental condition with a virtual dynamometer in the equivalent hand. None of the participants noticed that the dynamometer was not tracked since we attached the virtual dynamometer onto the skeleton of the avatar and, therefore, the rotation and translation of the avatars' wrist bones were transferred onto the 3D mesh of the dynamometer. Hence, we successfully created the illusion of tracking the dynamometer. The participants were instructed to stand on a virtual sign on the floor in front of the mirror and squeeze the dynamometer as strong as possible for five seconds. In line with the Southampton protocol (Roberts et al., 2011), the investigator instructed the participants with the words: "I want you to squeeze as hard as you can for five seconds. I will say stop after five seconds". The investigator started the task with a simple "Go". After five seconds, the investigator paused the VR application, took the dynamometer, handed over two weights for the left and right hand, and started a new scene.

In the isometric force task, the participants were instructed to remain at the same location in front of the mirror and to laterally raise the shoulder until the arms were slightly above horizontal. This position should be kept for 60 seconds holding both weights in the left and right hand maintaining a good posture in an upright position. The virtual RPE scale was presented throughout the task placed at the wall next to the virtual mirror. After 55 seconds the investigator asked the participants to indicate their physical exertion. Afterward, the investigator paused the VR application, took both weights, and started a scene with the next avatar to proceed with a one-minute exposition time. Each task was performed in a standing position. Neither verbal encouragement nor visual feedback regarding the performance outcome was given during the tasks. The participants spent about 45 minutes in VR resulting in a total time of approximately 60 minutes for the study.

5.3.7 Results

Our measures consist of non-parametric data. Shapiro-Wilk tests for normality were used to determine the assumption of normal distribution of all measures. Results show violations of normality for all measures ($p < .05$). Hence, we used the ARTool package for R by Wobbrock et al. (2011) to apply an ART ANOVA for hypothesis testing of

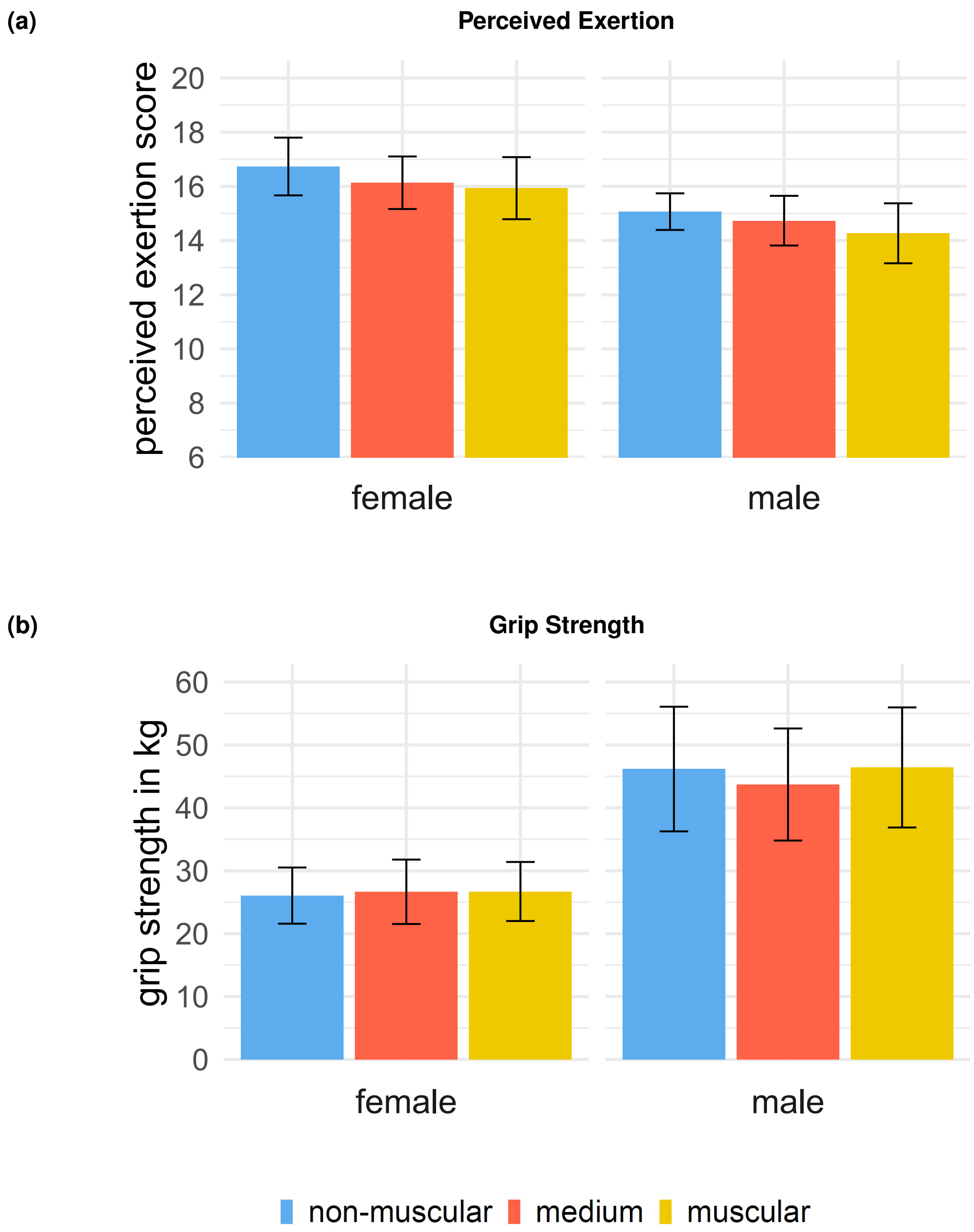

Figure 5.3: Average scores of the perceived exertion during the isometric force task (a) and the mean values of the grip strength measurements with a dynamometer (b). The error bars show the 95% confidence interval.

non-parametric data. Items of the BRQ concern ordinal data. Participation was entered as a random factor in all analyses. All pairwise cross-factor comparisons are Bonferroni-corrected.

5.3.7.1 Perceived Exertion

A multifactorial mixed-design ART ANOVA revealed a significant effect of GENDER, $F(1,28) = 4.476$, $p = .043$, $\eta_p^2 = .137$, and BODY, $F(2,56) = 3.978$, $p = .024$, $\eta_p^2 = .124$, on perceived exertion, however, there was no interaction effect of GENDER $\times$ BODY, $F(2,56) = 0.576$, $p = .565$, $\eta_p^2 = .020$. Although we found main effects of GENDER and BODY, pairwise comparisons using Wilcoxon signed-rank test were not able to reveal significant differences within GENDER and BODY (all $p > .05$). Hence, we additionally performed two univariate ART ANOVAs within the two independent groups *male* and *female*. There was no significant effect between the BODY levels of *male*, $F(2,28) = 2.963$, $p = .068$, $\eta_p^2 = .174$, and of *female*, $F(2,28) = 1.906$, $p = .167$, $\eta_p^2 = .119$. Thus, this is in line with the results of the multifactorial mixed-design ART ANOVA.

Additionally, we performed a multivariate linear regression analysis of each subdimension of the BRQ and could not find a significant effect of the subdimensions, $p = .869$, on participants' perceived exertion. Figure 5.3a shows the mean values of the perceived exertion assessed by the RPE scale.

5.3.7.2 Grip Strength

A multifactorial mixed-design ART ANOVA revealed a significant effect of GENDER, $F(1,28) = 21.084$, $p < .001$, $\eta_p^2 = .429$, and BODY, $F(2,56) = 3.430$, $p = .039$, $\eta_p^2 = .109$, on grip strength. There was no interaction effect of GENDER $\times$ BODY, $F(2,56) = 1.338$, $p = .271$, $\eta_p^2 = .045$. Although we found main effects of GENDER and BODY, pairwise comparisons using Wilcoxon signed-rank test were not able to reveal significant differences within GENDER and BODY (all $p > .05$). Hence, we additionally performed two univariate ART ANOVAs within the two independent groups *male* and *female*. Here, we found a significant effect between the BODY levels of *male*, $F(2,28) = 4.120$, $p = .027$, $\eta_p^2 = .227$, and not of *female*, $F(2,28) = 1.525$, $p = .235$, $\eta_p^2 = .098$. Subsequent pairwise comparisons using Wilcoxon signed-rank test revealed significant differences between *male muscular* and *male medium* avatars ($p = .014$), however, no significant

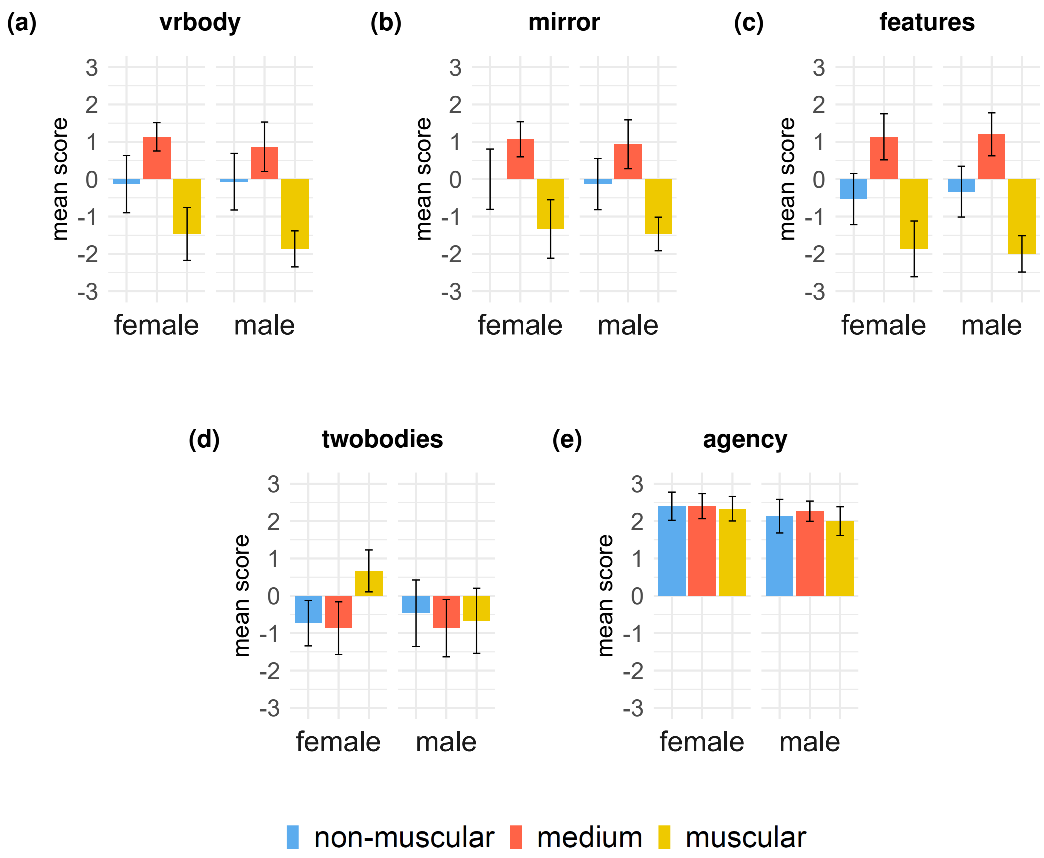

Figure 5.4: BRQ scores on body ownership for each subdimension (vrbody, mirror, features, twobodies, agency). The error bars show the 95% confidence interval.

differences were found in other pairwise comparisons (all $p > .05$). Thus, we assume an interaction effect between GENDER × BODY and suppose a Type II error in the multifactorial mixed-design ART ANOVA.

Additionally, we performed a multivariate linear regression analysis of each subdimension of the BRQ and could not find a significant effect of the subdimensions, $p = .223$, on male participants' grip strength. Figure 5.3b shows the average grip strength measurements.

5.3.7.3 Body Ownership

To detect significant differences in the illusion of body ownership for each avatar, we performed multiple multifactorial mixed-design ART ANOVAs on each subscale of

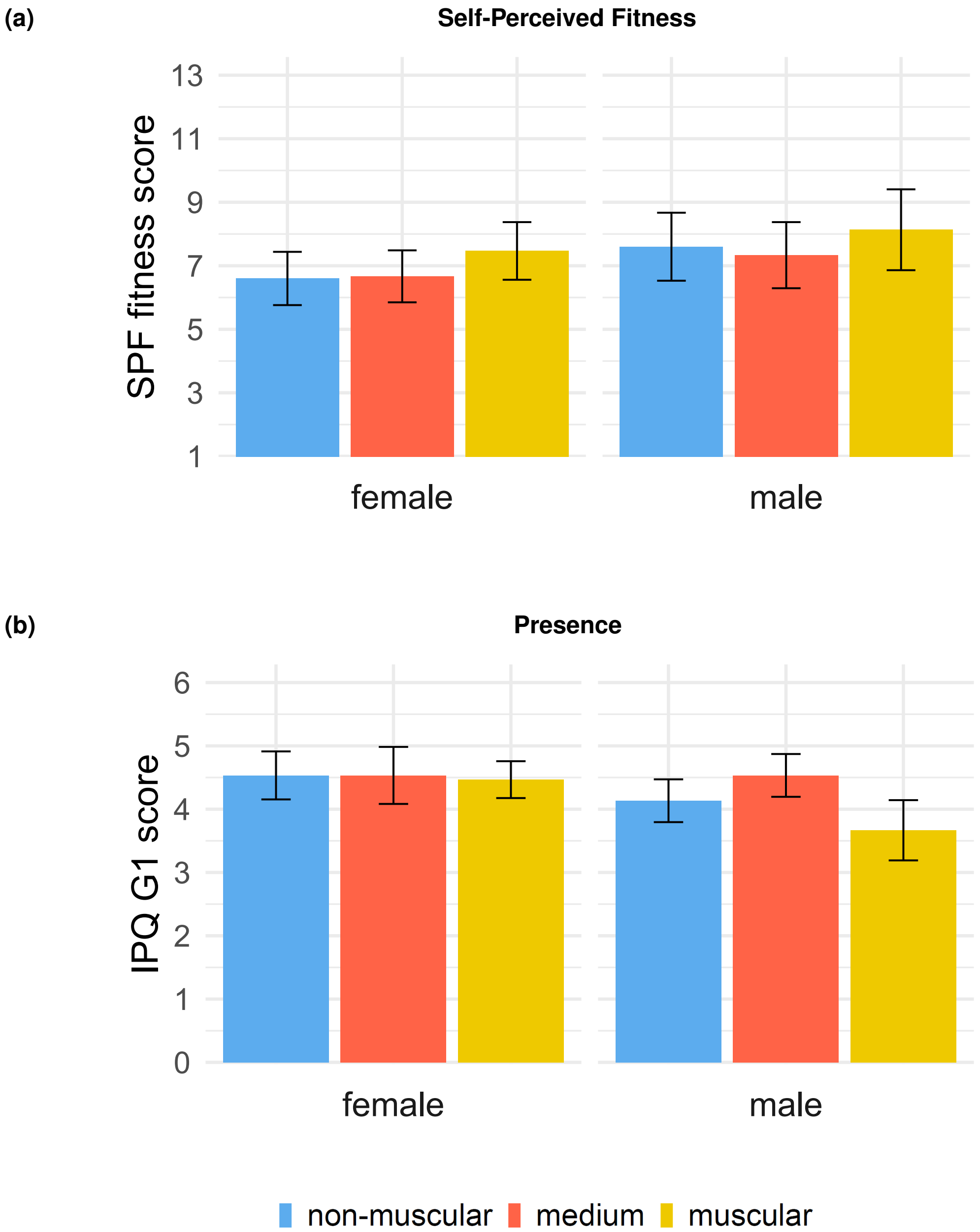

Figure 5.5: Average scores of the subscale fitness of the SPF questionnaire (a) and the general presence (item G1) of the IPQ (b). The error bars show the 95% confidence interval.

the BRQ. We did not find a significant effect of GENDER, $F(1,28) = 0.148$, $p = .702$, $\eta_p^2 = .005$, on the subscale *vrbody*, however, we found a significant effect of BODY, $F(2,56) = 29.772$, $p < .001$, $\eta_p^2 = .515$. There was no interaction effect of GENDER × BODY, $F(2,56) = 0.450$, $p = .639$, $\eta_p^2 = .015$. Pairwise comparisons using Wilcoxon signed-rank test within BODY revealed significant differences between *non-muscular* and *medium* ($p = .010$), *non-muscular* and *muscular* ($p = .002$), and *medium* and *muscular* ($p < .001$) avatars.

GENDER, $F(1,28) = 0.036$, $p = .850$, $\eta_p^2 = .001$, had no significant effect on *mirror*, however, we found a significant effect of BODY, $F(2,56) = 30.770$, $p < .001$, $\eta_p^2 = .523$. There was no interaction effect GENDER × BODY, $F(2,56) = 0.111$, $p = .895$, $\eta_p^2 = .003$. Pairwise comparisons using Wilcoxon signed-rank test within BODY showed significant differences between *non-muscular* and *medium* ($p = .003$), *non-muscular* and *muscular* ($p = .001$), and *medium* and *muscular* ($p < .001$) avatars.

We found no significant effect of GENDER on *features*, $F(1,28) = 0.033$, $p = .856$, $\eta_p^2 = .001$, however, there was a significant effect of BODY, $F(2,56) = 48.427$, $p < .001$, $\eta_p^2 = .523$. We did not find an interaction effect of GENDER × BODY, $F(2,56) = 0.095$, $p = .908$, $\eta_p^2 = .003$. Pairwise comparisons using Wilcoxon signed-rank test within BODY showed significant differences between *non-muscular* and *medium* ($p < .001$), *non-muscular* and *muscular* ($p < .001$), and *medium* and *muscular* ($p < .001$) avatars.

We found no significant effect of GENDER on *twobodies*, $F(1,28) = 0.490$, $p = .489$, $\eta_p^2 = .017$, however, there was a significant effect of BODY, $F(2,56) = 6.094$, $p = .004$, $\eta_p^2 = .178$. We found an interaction effect of GENDER × BODY, $F(2,56) = 5.984$, $p = .004$, $\eta_p^2 = .176$. Pairwise comparisons using Wilcoxon signed-rank test revealed significant differences between *female medium* and *female muscular* ($p = .009$), and *female non-muscular* and *female muscular* ($p = .005$). There were no significant differences between all *male* avatars (all $p > .05$).

There was neither a significant effect of GENDER, $F(1,28) = 0.911$, $p = .347$, $\eta_p^2 = .031$, BODY, $F(2,56) = 0.818$, $p = .446$, $\eta_p^2 = .020$, nor an interaction effect of GENDER × BODY, $F(2,56) = 0.061$, $p = .940$, $\eta_p^2 = .002$, on *agency*. Figure 5.4 shows the average scores of each dimension of the BRQ.

5.3.7.4 Self-Perceived Fitness

A multifactorial mixed-design ART ANOVA could not show a significant effect GENDER, $F(1,28) = 1.047$, $p = .315$, $\eta_p^2 = .036$, on the subscale *fitness*, however, there was a

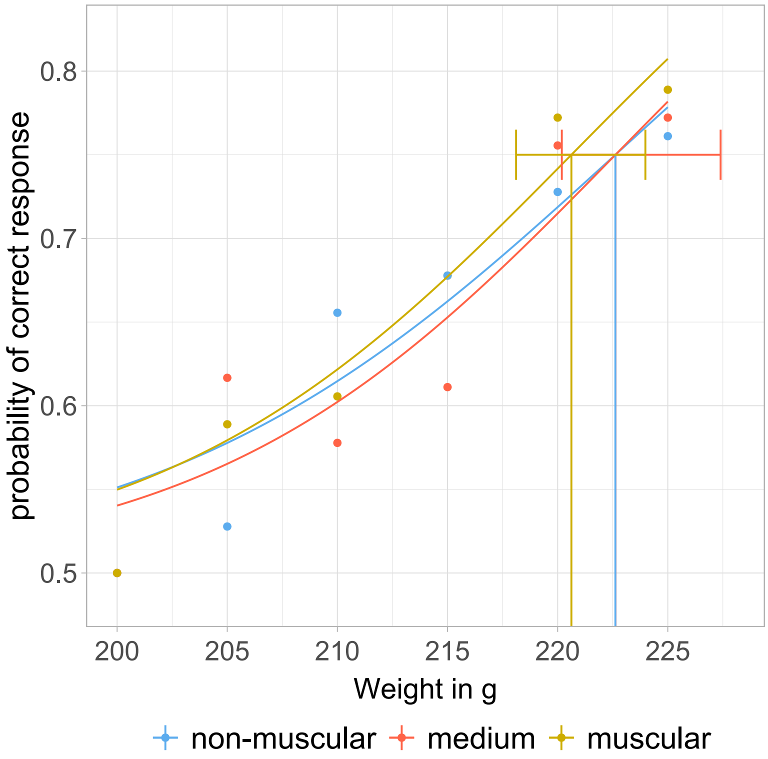

Figure 5.6: Psychometric functions and JNDs (75%) of all conditions based on the fitted Weibull cumulative distribution. The y-axis represents the probability of correctly choosing the heavier weight. The error bars show the 95% confidence interval. Participants in the muscular avatar condition had a lower JND than in the non-muscular and medium condition.

significant effect of BODY, $F(2,56) = 7.034$, $p = .001$, $\eta_p^2 = .200$. We did not find an interaction effect of GENDER × BODY, $F(2,56) = 0.343$, $p = .711$, $\eta_p^2 = .012$. Pairwise comparisons using Wilcoxon signed-rank test within BODY found a significant effect of the *non-muscular* and *muscular* ($p = .016$), and *medium* and *muscular* ($p = .012$) avatars. We did not find any further effects of GENDER and BODY on the subscales *endurance*, *strength*, *flexibility*, and *body composition* (all $p > .05$). Participants perceived themselves as physically fitter embodying the *muscular* avatar than the *non-muscular* and *medium* avatar (see Figure 5.5a).

5.3.7.5 General Presence

We performed a multifactorial mixed-design ART ANOVA and did not find a significant effect of GENDER on general presence, $F(1,28) = 3.910$, $p = .057$, $\eta_p^2 = .122$, however, there was a significant effect of BODY, $F(2,56) = 6.451$, $p < .003$, $\eta_p^2 = .187$. We also found an interaction effect of GENDER $\times$ BODY, $F(2,56) = 3.214$, $p = .047$, $\eta_p^2 = .102$. Pairwise comparisons using Wilcoxon signed-rank test revealed a significant difference between *male medium* and *male muscular* ($p = .038$). Other pairwise comparisons were not significant (all $p > .05$). Male participants felt less present in the VE when embodying the *muscular* avatar compared to the *medium* avatar (see Figure 5.5b).

5.3.7.6 Just-Noticeable Difference

We used the R package quickpsy (Linares & López-Moliner, 2016) to fit psychometric data using Weibull cumulative distribution function (two free parameters, 0% lapse rate). We considered the constant stimulus (200 g) as the point of subjective equality assuming a 50% probability of a correct response at chance (the 50% criterion value). We applied a maximum-likelihood model as fitting criteria with a 75% threshold as the JND. This is the threshold at which participants correctly decided for the heavier weight in 75% of the trials. To estimate the 95% confidence intervals, we performed a non-parametric bootstrap with 1000 trials (Linares & López-Moliner, 2016). Figure 5.6 depicts the psychometric functions for each condition. A comparison of the means indicates a lower JND for the *muscular* avatar ($M = 20.62$ g, $SD = 2.03$ g) compared to the *non-muscular* ($M = 22.62$ g, $SD = 4.19$ g) and *medium* ($M = 22.62$ g, $SD = 5.67$ g) avatars. Since previous work showed that the JND of males and females does not differ relatively (Haile et al., 2013), we calculated the JNDs combining the data of male and female subjects per condition. Due to the number of samples per participant, we could not fit a function to obtain individual JNDs and, therefore, we did not perform any inferential statistical analysis. Consequently, we only provide descriptive statistics.

5.3.8 Discussion

The data of our experiment showed a significant effect of avatars' muscular appearance on users' perceived exertion during physical effort. Furthermore, we found that male participants embodied in a muscular avatar had a higher grip strength compared to being in a medium avatar in immersive VR.

To explain these effects, we refer to prior research that supports the notion that the type of the avatar's body triggers expectations of what it would be like to own such a body (Banakou et al., 2013; Banakou et al., 2018). Since the brain is able to adapt to changes in the body structure to compensate for the discrepancy between the real and the avatar's body and to integrate the "new" body features into the own body schema (Moseley et al., 2012; Llobera et al., 2013), we accept the virtual body as our own and behave in accordance to common expectations connected to the type of body (Yee, 2007). Since participants embodied in a muscular avatar are expected to perform better in physical tasks than in avatars with a less muscular body physique (Suchomel et al., 2016), we assume that their "new self" motivates and engages the users and, therefore, increases physical performance in terms of perceived exertion and grip strength.

In our study, we investigated the effect of avatars' muscular appearance when being alone in VR. In contrast to Barathi et al. (2018) and Koulouris et al. (2020), we have to consider our effects isolated from reciprocal influences of multiple avatars based on interactive feedforward methods. The authors have already identified self-modeling as an effective intervention procedure to enhance players' physical performance in a competitive exergame, where players raced against their improved version. However, Koulouris et al. (2020) also found that idealized avatars as competitors may even have a negative impact on players' performance. This is in line with Peña and Kim (2014) who showed that physical activity can decrease when the players think that their avatar has a physical advantage or disadvantage over the opponents' avatar. They referred to it as the "take it easy" and "give up" hypothesis (Peña & Kim, 2014). Thus, results from these studies imply that being and interacting with another avatar might have additional effects such as the impact of social presence, competition, or self-discrepancy (Koulouris et al., 2020) that may confound embodiment effects caused by the visual appearance of avatars on physical performance. Due to the ambiguous findings from previous work, more research is needed to back up our results.

5.3.8.1 Perceived Exertion

The perceived exertion during the isometric force task with shoulder abduction was assessed by the RPE scale. The ratings suggest that the task was less physically demanding for participants embodied in a muscular avatar. Even if they performed the same exercise, participants perceived the task as more exhausting and physically intense embodied in a non-muscular avatar.

The findings suggest that the muscular appearance of avatars can systematically affect the conscious sensation of effort exerted during a physical exercise. Since the perception of effort can fundamentally determine pace and performance in physical tasks (de Morree & Marcora, 2015), endurance performance (Pageaux, 2014), adherence to exercise programs, and physical acitivity (Marcora, 2016; Pageaux, 2016), this could pose an opportunity for exergame designers to decrease players' perceived exertion by changing the avatars' muscular appearance. Based on the work by Wiemeyer (2019), who created an interdisciplinary framework to evaluate the efficacy of fitness applications, further studies are needed to investigate whether the muscular appearance of avatars can be utilized to design more effective exergames.

5.3.8.2 Grip Strength and Body Ownership

We could not find a systematic influence of the muscular appearance of the avatar on grip strength. We hypothesized that the grip strength increases with the embodiment of our avatars from non-muscular to muscular, when in fact male participants embodied in the non-muscular avatar tended to have a higher grip strength than embodied in the medium avatar. Since previous work revealed that the extent of the illusion of body ownership can moderate the Proteus effect (Banakou et al., 2013; Osimo et al., 2015; Ahn et al., 2016; Yoon & Vargas, 2014), the induced BOI could potentially affect the grip strength. However, there was no effect of the body ownership ratings on grip strength and perceived exertion, that is why we assume that both measures are not functions of the experienced body ownership.

Considering the scores of the BRQ's subdimensions and the general presence which were generally low, we induced the strongest BOI and presence in the medium avatar indicating that the medium avatar most resembles the participants' physical body and their body physique, thus serving as an appropriate baseline. In line with the perceived exertion, we should have observed that participants embodied in the non-muscular avatar have a lower grip strength compared to that when embodied in the medium avatar, which was not the case. Equally high agency ratings for all avatars indicating a high sense of motor control rule out effects caused by technical limitations, for example tracking issues or drops in framerate.

A possible explanation why male participants embodied in the non-muscular avatar did not have a lower grip strength compared to the medium avatar could be the shape of the body and the connected associations of users. The SPF in our analysis serves as a manipulation check indicating that the muscular avatar was considered to be the fittest with the non-muscular avatar tending to have a better perceived fitness than the medium avatar. This is in line with our results regarding the measurement of grip strength. Hence, the non-muscular body type of the avatar could still be perceived as too fit and athletic due to low body fat rather than being associated with physical weakness. Future work should focus on conducting a study to determine what stimuli should be used to explicitly represent strength and power on the one hand, and physical weakness and the characteristic of being unathletic on the other.

5.3.8.3 Gender Differences in the Body Image

Interestingly, grip strength could not be enhanced for female participants by embodying a muscular avatar. According to self-perception theory, the evaluation of the avatar from an imaginary third-person perspective and the resulting associations have to be linked with the user's self to allow the Proteus effect to occur (Bem, 1972; Yee, 2007; Reinhard et al., 2020). Koulouris et al. (2020) showed in their study that women considered their athletic version of themselves as slimmer than that of male participants, who customized their avatars with a more muscular physique. This could be potentially explained by gender differences in the body image—the subjective perception and beliefs about the own body (Calogero & Thompson, 2010).

Previous work found that women evaluate the fitness of their own body in a different way than men (Kumar et al., 2016). The idealized image of the male body consists of extreme muscles and a lean body physique (Botta, 2003; Calogero & Thompson, 2010; Leon et al., 1999) with an ideal body about 13 kg more muscular than their own (Pope et al., 2000). On the contrary, women tend to idealize a "curvaceously" thin body (Harrison, 2003) with even negative emotions connected with athletic or hypermuscular bodies (Voges et al., 2019). Even if the muscular avatar is perceived as physically fit according to the SPF questionnaire, the features of the avatar's body may not be desirable for women causing a lack of engagement and excitement to a greater extent than normal. Hence, the idealized version of females perceived to be athletic and physically strong in a motivating manner seems not to match with our avatars, that is why we assume that the avatars' characteristics could not be connected with the user's self. Since user identification and wishful identification foster intrinsic motivation (Birk et al., 2016) resulting in more motivated behavior and better performance (Birk et al., 2016; Koulouris et al., 2020; Ioannou et al., 2019; Waltemate et al., 2018), the lack of identification with the female muscular and non-muscular avatar could be a factor that the avatars did not affect grip strength. Future work should analyze user identification and the BOI as moderators of embodiment effects caused by the avatar, since it is yet unknown how and in particular to what extent these concepts mediate effects on the embodying user. Therefore, objective measures to assess the participants' physical conditions such as the Body Mass Index (BMI) and the body weight should be measured to complement subjective ratings such as the SPF.

5.3.8.4 Just-Noticeable Difference

Based on results of prior work by Schwind et al. (2018a), who investigated the effect of virtual limb ownership in a visual-haptic integration task and found an effect of hand embodiment on the JND, we used the JND task to get first insights into the relationship of full-body ownership and the sensitivity to weight discrimination. Descriptive statistics show that users embodied in muscular avatars had a higher sensitivity to weight discrimination than users owning a non-muscular or medium avatar. According to the BRQ ratings, participants indicated to have the lowest BRQ scores in the muscular body, thus we assume that the user's weight perception in VR could be affected by the variation of the degree of BOI due to the muscular appearance of avatars. Since our sample size does not allow inferential statistics on individual level, in future work we aim to repeat the experiment with a larger sample and individual JNDs to investigate whether the variation of the degree of body ownership changes users' weight perception.

5.3.9 Conclusion

In this section, we investigated the effects of avatars with a different muscular appearance on the perception of effort, physical performance, and weight perception. Thirty participants performed three different tasks. First, we investigated the sensitivity to weight discrimination by identifying the JND in a psychophysical experiment using a 2AFC task. Second, we measured the participants' grip strength using a dynamometer. Finally, we assessed the perceived exertion during an isometric force task. We also integrated questionnaires in VR to measure the SPF, the sense of presence, and the BOI. We assume that the muscular appearance of avatars can affect the perceived exertion of the embodying users during physical tasks. Under the limitation that we could not find an enhancement of female participants' grip strength, results suggest that the avatars' muscular appearance can affect the physical performance of male users. More research is needed to consolidate the findings as they may provide an opportunity for designers of VR exergames to take advantage of the avatars' muscular appearance in short-time physical tasks to make players perform better than they would in a casual virtual embodiment. Hence, this could result in enhanced exercise benefits and contribute to more effective and successful exergames. Future work should also explore the contribution of concepts like body ownership, user identification, and user motivation to get deeper insights into the underlying mechanisms.

5.4 Study II: Athletic Appearance

In the previous section, we learned that muscular avatars can reduce the perception of effort. Hence, users embodied in muscular avatars perceived a physical task as less intense compared to a non-muscular and medium avatar. The perception of effort was assessed using the RPE scale (Borg, 1982), which was originally designed to estimate the HR. For example, a score of 11 (light exertion) should approximately match a HR of 110. Due to the correlation between HR and perception of effort, we investigated in a second study if the embodiment of "high-performing" avatars can even affect physiological responses. Hence, we explored the psychophysiological impact of avatars on users. We, therefore, asked participants to ride a stationary bicycle using a standardized exercise protocol (Northridge et al., 1990) and three systematically designed avatars. We measured participants' HR, perceived exertion, pedaling frequency, and the covered distance. We also assessed identification with the avatar, SPF, and body ownership.

5.4.1 Psychophysiological Effects during Physical Effort

To learn about psychophysiological effects in physical settings, we reviewed research in sports psychology that provides evidence for a variety of psychophysiological effects on professional and amateur athletes during exertion. Lautenbach et al. (2019), for example, concluded that high-fives can decrease stress in terms of a lower cortisol level during physical effort. A similar effect can occur while listening to music. Brownley et al. (1995) found that fast, upbeat music can positively affect an athlete's physiological responses while running. This is in line with Patania et al. (2020), who showed advantageous effects of music on HR and perception of effort in endurance exercises. The authors explained the effects of music's ability to distract from negative feelings caused by exertion, such as discomfort, fatigue, or pain, and address the brain's emotion and reward system (Altenmüller & Schlaug, 2013). This attentional shift from negative responses in combination with an increased amount of pleasure during exertion could also be found in group exercises, which are associated with reduced dropout rates (Vandoni et al., 2016). Furthermore, mental imagery interventions in sports are an effective psychological tool to enhance performance in terms of muscular power (Slimani & Chéour, 2016), endurance (McCormick et al., 2015), and physiological responses to physical effort (Simonsmeier et al., 2020; Slimani et al., 2016; Wang & Morgan, 1992).

Decety et al. (1991) showed, for example, that the pure mental imagination of physical effort could increase the participants' HR and that this rise in HR even correlated with a higher intensity relative to the real physical effort. According to Giacobbi et al. (2003), appearance imagery is one of the main types of mental imagery in exercises and describes the self-visualization with an improved physical appearance (Razon et al., 2014). Razon et al. (2014) found that participants using mental imagery techniques had a higher lactic acid level while cycling compared to participants without self-visualization. Based on these findings, the authors concluded that mental imagery could make the participants put more effort into physical tasks. Overall, results suggest that psychophysiological effects can induce behavioral and perceptual changes during exercise, which in turn can potentially influence physical performance. VR allows to vividly visualize how it would feel to have a body with an improved physical appearance. However, it is unclear whether similar effects on users' physiological responses to physical exertion can be induced using athletic avatars in VR.

5.4.2 Avatar Selection

Analyzing the effects of an avatar's athletic appearance during physical exertion requires avatars with different levels of expected physical fitness. Therefore, we conducted an initial study to systematically determine three male- and female-gendered avatars that range from being athletic on one end to unathletic on the other.

5.4.2.1 Stimuli

We designed 16 female- and 16 male-gendered avatars using the 3D-suite Daz3D. The avatars are based on the characters Genesis 8 Male and Female. We used the two primary fitness indicators body fat and muscle proportion (Durkee et al., 2019; Sell et al., 2009) as dimensions to adapt the athletic appearance of the avatars. We started at 0% for each dimension and systematically increased the avatar's body fat and muscles by 33% using morph targets resulting in the 16 male- and 16 female-gendered avatars. We placed the avatars on a 3D model of a stationary bicycle in front of a virtual mirror and rendered the scenes in first-person perspective (see Figure 5.7).

As our study investigated performance in a physical exercise task, it uses measures dependent on biological sex characteristics. This necessitated designing female and male avatars. In the world of sports, there is a clear distinction between genders based on hormone levels, and this distinction is linked to performance (IAAF, 2018). Female cyclists compare at different distances and speeds than male cyclists (Sanders et al., 2018). Consequently, our study asked participants directly about their biological sex, based on their hormone levels[1]. All of the participants identified as cisgender.

5.4.2.2 Survey Design and Measures

We conducted an online survey using a within-subjects design with the independent variable BODY. The participants were presented with the renderings of the avatars of their previously reported gender in a randomized order. They were asked to imagine being the displayed avatar riding a stationary bike and to answer the questions from the avatar's perspective. Participants rated the perceived fitness of the avatars on a 13-point scale with an ascending level from 1 to 13 using the SPF questionnaire (Delignières et al., 1994). Additionally, they estimated the resting HR ranging from 40 and 240 beats per minute (bpm) and the HR while riding a stationary bike for 10 minutes with 16 miles per hour (mph; ranging from 40 to 240 bpm). They also estimated the time required while cycling as fast as possible for 5 miles (ranging from 5 to 120 minutes) and the avatar's speed while cycling for 10 minutes with a HR of 120 bpm (ranging from 5 to 50 mph). These measures were used to determine the avatars' perceived fitness and performance on a stationary bicycle. We also assessed whether the avatars resembled the participants ("It feels as if the character is me") using a 7-point Likert item. Before the avatar ratings, participants were asked to report demographic data as well as their physical activity level using the SPF questionnaire. The survey took about 20 minutes.

[1] In line with the SIGCHI gender guidelines, `https://www.morgan-klaus.com/gender-guidelines.html#Health-Research`

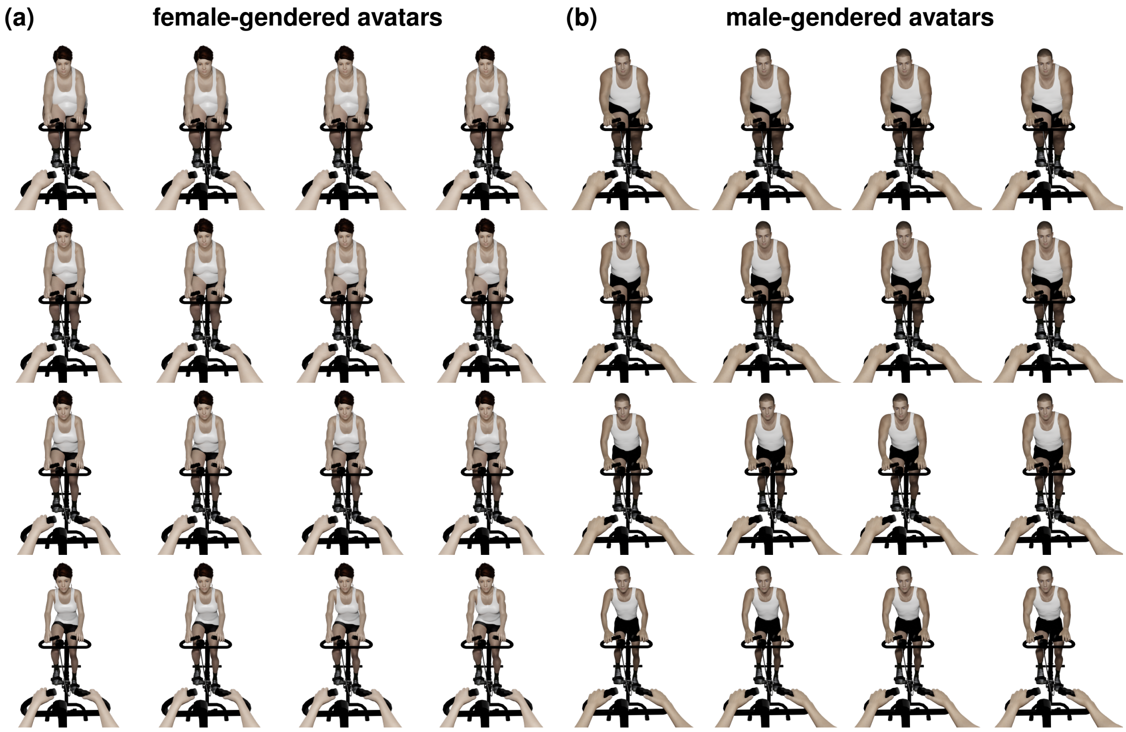

Figure 5.7: Renderings of the 32 avatars for the online survey with an increasing proportion of body fat (0%, 33%, 66%, 100%) from bottom to top and an increasing proportion of muscularity (0%, 33%, 66%, 100%) from left to right for the female-gendered (a) and the male-gendered (b) avatars.

5.4.2.3 Participants

We recruited 74 participants (36 female, 38 male) via the paid crowdsourcing platform Amazon Mechanical Turk. Human Intelligence Task (HIT) requirements were set to an approval rate of $> 98\%$, > 500 approved HITs, and within the US. Participant age ranged from 22 to 68 ($M = 40.76$, $SD = 11.47$). We offered \$2 for completing the survey.

5.4.2.4 Results

Estimated resting HR, HR while cycling, achieved speed, and required time are shown in Figure 5.8. Within each gender, we observed similar patterns for all measures. We started creating the avatars by averaging the measures for each of them. Afterward, we determined the female- and male-gendered avatar with the highest and lowest overall

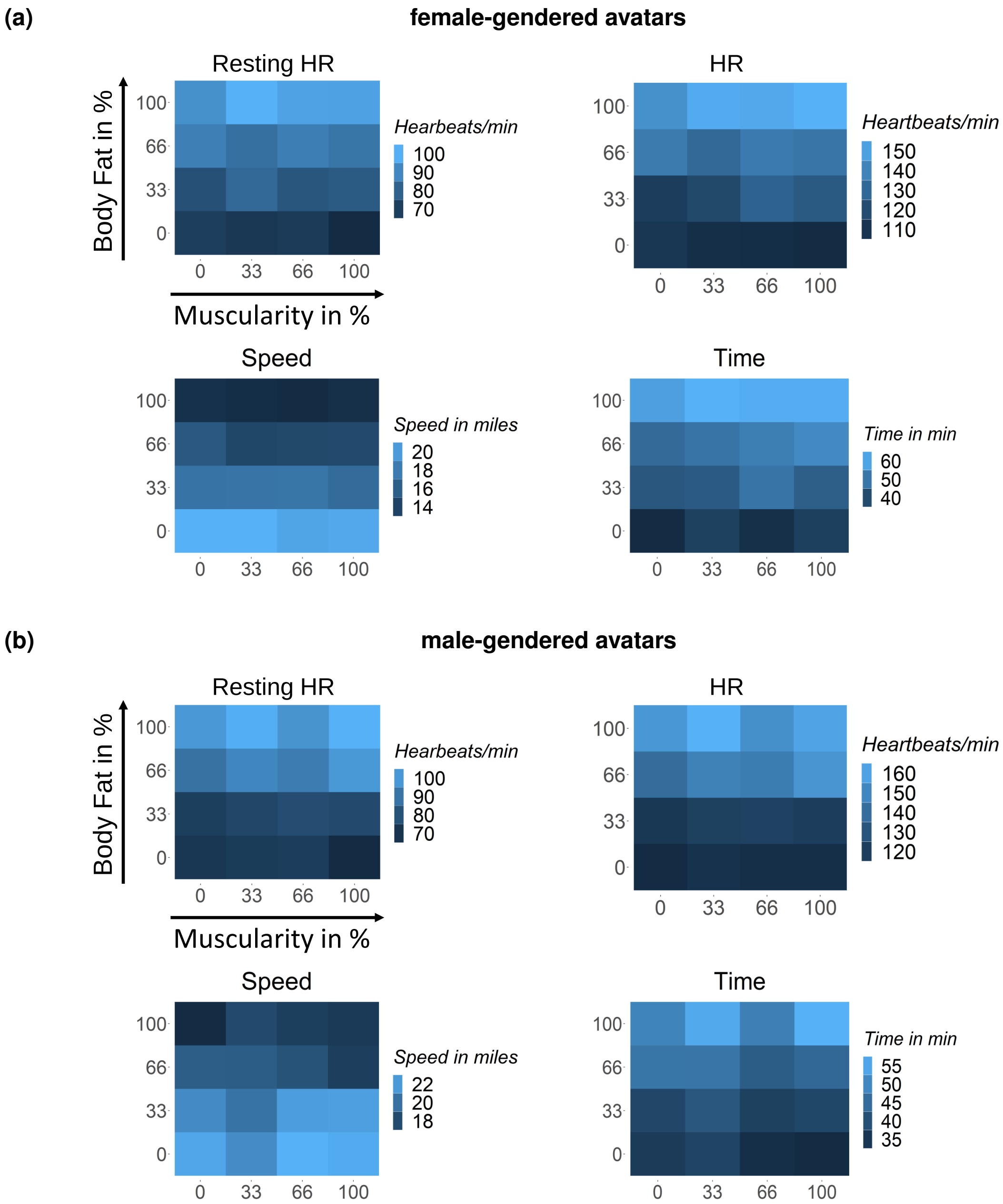

Figure 5.8: Heatmaps depicting the average scores of each measure assessed in the online survey for the female-gendered (a) and the male-gendered (b) avatars. The y-axis represents the proportions of body fat (0%, 33%, 66%, 100%) and the x-axis the proportions of muscularity (0%, 33%, 66%, 100%). Based on these scores per measure, we defined three female and three male avatars with different levels of athleticism.

Figure 5.9: The real world (left) and the virtual scene consisting of the non-athletic, the medium, and the athletic avatars (from left to right) on a stationary bicycle.

performance resulting in the most and the least athletic avatar for both genders. Based on these avatars, we designed the respective medium avatar by determining the equidistant difference of body fat and muscularity between the athletic and medium, and medium and non-athletic versions. For the male-gendered avatars, we used 66% body fat with 0% muscularity for the non-athletic, 33% body fat with 33% muscularity for the medium, and 0% body fat with 66% for the athletic version. To design the female-gendered avatars, we used 66% body fat with 33% muscularity for the non-athletic, 33% body fat and 33% muscularity for the medium, and 0% body fat with 66% muscularity for the athletic version. The final avatars are shown in Figure 5.9.

5.4.3 Study Design

To investigate the effects of the avatars' athletic appearance, we conducted a study using a within-subjects design with the independent variable BODY with the three levels *non-athletic*, *medium*, and *athletic*. Hence, participants embodied avatars of their identified gender with a different athletic appearance. To reduce order effects, we counterbalanced the order of the avatars using a 3×3 Latin square.

5.4.4 Measures

While the participants were riding a stationary bicycle, we assessed the perceived exertion using the RPE scale (Borg, 1982). We also measured the HR while cycling and during the resting periods after each condition. Furthermore, the covered distance and the pedaling frequency were measured to determine the rate at which the participants were turning the pedals. In addition to performance measures, participants were also asked to complete questionnaires after each condition such as the SPF questionnaire (Delignières et al., 1994), the BRQ (Banakou et al., 2013; Banakou et al., 2018) for quantifying the experienced body ownership, and the subscales for similarity identification, embodied presence, and wishful identification from the Player Identification Scale (PIS; Looy et al., 2012) to measure the participants' presence and identification with the avatars.

5.4.4.1 Perceived Exertion

Based on a well-established experimental procedure (Borg, 1962; Borg, 1982; Borg, 1990), we determined the perceived exertion while riding a stationary bicycle. The participants were shown a visual scale—the psychophysical Borg's RPE scale (Borg, 1982)—at four different points in time—after 4:45, 9:45, 14:45, and 19:45 minutes. The participants orally communicated the value that best represented their perception of effort. The RPE scale was designed to increase linearly with physical exercise intensity ranging from 6 (no exertion) to 20 (maximal exertion). The scale is designed to approximately estimate the current HR by multiplying each value by 10, so that an intensity of 15, for example, approximately matches a HR of 150 (Borg, 1982).

5.4.4.2 Heart Rate

Since the HR is frequently used as a predictor for one's level of physical fitness (Silva et al., 2018; Sandvik et al., 1995; Plasqui & Westerterp, 2006; Olsson et al., 2020), we measured the HR using an optical HR monitor worn at the participant's arm (Polar OH1, Polar Electro, Kempele, Finland) which can be employed as a valid measurement device during moderate- and high-intensity physical activities (Hettiarachchi et al., 2019). We assessed the HR throughout the experiment to get insights into the HR response while cycling and in the resting periods after each condition.

5.4.4.3 Pedaling Frequency

To investigate behavioral changes caused by the visual appearance of the avatars, we used the pedaling frequency (in revolutions per minute, rpm) as a dependent variable. We attached a cadence sensor (Polar Cadence Sensor Bluetooth Smart, Polar Electro, Kempele, Finland) on the stationary bicycle to measure the pedaling rate per minute.

5.4.4.4 Body Ownership

To quantify the induced body ownership, we used the BRQ (Banakou et al., 2013; Banakou et al., 2018) with the single-item subscales vrbody ("I felt that the virtual body I saw when looking down at myself was my own body"), mirror ("I felt that the virtual body I saw when looking at myself in the mirror was my own body"), features ("I felt that the virtual body resembled my own real body in terms of shape, skin tone or other visual features"), twobodies ("I felt as if I had two bodies"), and agency ("I felt that the movements of the virtual body were caused by my own movements").

5.4.4.5 Self-Perceived Fitness

We used a version of the self-appraisal questionnaire by Borg et al. (1972) adapted by Delignières et al. (1994) to assess the SPF per condition serving as a manipulation check. The authors created a questionnaire with the five dimensions endurance, strength, flexibility, body composition, and fitness rated on a 13-point scale with an ascending level ranging from 1 to 13 (Delignières et al., 1994).

5.4.5 Apparatus

We used three male and three female avatars with different athletic appearance (see Figure 5.9). Each avatar model had the same skeleton with an identical configuration of bones. We used the game engine Unity3D (v. 2019.3.11f1) to implement the VR application. To allow the participants to focus on their virtual body, we used a simple virtual scene only consisting of a fitness room with dark walls, a stationary bicycle, and a mirror with stereoscopic reflections. We placed an electromagnetically braked bicycle ergometer (SportPlus Ergometer, Latupo GmbH, Hamburg, Germany) in our VR laboratory. We used the watt mode so that the ergometer dynamically adjusted resistance based on a given watt value resulting in a speed-independent workload. An HTC Vive tracker was firmly attached to each pedal using cable ties to register and transfer the pedal motion onto the virtual replica of the ergometer in the VE. We substituted the participants' real body by the non-athletic, medium, and athletic avatar using an HTC Vive HMD with a wide horizontal field of view of 100° and a spatial resolution of $1080 \times 1{,}200$ pixels per eye displayed at 90 FPS. The participants perceived the VE and their virtual bodies from a first-person perspective. We placed a virtual mirror into the scene so that they could constantly perceive their virtual body while riding the bicycle ergometer. To track the participants' pedaling motion and transfer the leg postures onto the virtual skeleton of the avatars, we used real-time inverse kinematics[1]. We used an Android smartphone running the Polar Beat app compatible with the Polar HR sensor (Polar OH1, Polar Electro, Kempele, Finland) to measure the participants' HR. The VR application ran on a Dell G5 15 notebook PC (Windows 10, Intel i7-8750H, 8GB RAM, NVIDIA GeForce RTX 2060 Mobile graphics card).

5.4.6 Participants

We recruited 24 participants (12 female, 12 male) via a mailing list of our institution. Their age ranged from 23 to 33 years ($M = 28.33$, $SD = 2.63$). To assess the participants' level of fitness, we used the SPF questionnaire by Delignières et al. (1994) as part of the demographic questionnaire. In addition, we calculated the individual BMI ($M = 22.74$, $SD = 2.61$) based on the participant's body weight and height, and determined their maximum HR ($M = 191.67$ bpm, $SD = 2.63$ bpm) using the age-predicted HR_{max} equation (i.e., $220 - age$; Tanaka et al., 2001). None of the participants owned a VR device but 10 participants already experienced VR before the study. No participant reported any pain in the legs before and after the study. Participants were informed that they could withdraw or discontinue participation at any time without penalty.

5.4.7 Procedure

Due to the COVID-19 pandemic, our government and institution developed hygienic regulations which we followed throughout the study. Based on our proposed hygienic measures (Kocur et al., 2020d), we specified and implemented additional safety measures for our laboratory, which were approved by our institution, e.g., thorough disinfection of

[1] https://assetstore.unity.com/packages/tools/animation/final-ik-14290

HMDs with a “three-day quarantine” after usage, extensive ventilation of the laboratory, and detailed hygiene instructions for the experimenter such as wearing a face mask and gloves during the experiment.

First, we provided an introduction to the hygiene measures followed by questions about the participants’ health conditions. If there were no indications of health concerns, the participants signed an informed consent form and completed the demographics questionnaire. Afterward, they were given a brief introduction to VR and could get familiar with the VR equipment. Before starting the experiment, the participants could change their clothes and put on sportswear in a separate room in our laboratory. We attached the optical HR sensor onto the participants’ forearm.

After the participants sat on the bike, we helped them with putting on the HMD, adjusted it to their head, and calibrated the interpupillary distance to ensure the best visual results. The height of the bike’s seat was adjusted so that the participants’ knees were slightly bent when the pedals were at the bottom position. As we only tracked the motion of the pedals and used inverse kinematics to animate the legs and the torso, we asked them to remain in a comfortable position during cycling with their arms holding the handlebars. We started the scene and embodied the participants in the first avatar condition as soon as they entered VR. At the beginning of each condition, there was a five-minute warm-up phase where the participants were asked to slowly pedal at a constant low-intensity load of 40 watts. Based on a standardized exercise protocol frequently used in clinical settings (Northridge et al., 1990), we started the exercise phase at 50 watts and increased the workload by 10 watts every minute. After 10 stages (= 10 minutes) with a workload of 140 watts in the last stage, we included a five-minute cool-down phase again with a constant workload of 40 watts resulting in a total exercise time of 20 minutes per avatar condition. Thus, we ensured that the exercise intensity was identical for each avatar condition within the aerobic threshold of 75% of the maximum HR to avoid the lactate turn point (Park et al., 2014).

Participants then took off the HMD, got off the bicycle, and completed the questionnaires on a notebook computer. Before the next avatar condition, we included a resting period of at least 4 minutes to ensure that the participants reach their baseline HR before starting the next avatar condition. At the end of the study, the participants were asked to give general feedback about the virtual experience and the avatars. Neither verbal encouragement nor visual feedback regarding the performance measures was given during the study. The participants spent 60 minutes in VR resulting in a total time of approximately 90 minutes for the study including hygiene measures.

5.4.8 Results

Our measures consist of parametric and non-parametric data. Shapiro-Wilk tests for normality were used to test the assumption of normal distribution for parametric data. Items of the BRQ and SPF questionnaire concern ordinal data. We used the ARTool package for R by Wobbrock et al. (2011) to apply an ART ANOVA for hypothesis testing of non-parametric data. The participant was entered as a random factor in all analyses. We included the avatars' GENDER as a between-subjects variable in the statistical analysis to control for effects of female and male avatars' athleticism. All pairwise post-hoc comparisons are Bonferroni-corrected.

To investigate the effects of the independent variable BODY on the participants' HR response, we analyzed the time course per minute of the HR across the entire exercise including warm-up and cool-down (see Figure 5.10). In line with Northridge et al. (1990), we calculated one-minute time intervals and included the factor TIME in the statistical analyses. Furthermore, we evaluated the average HR during the exercise and the resting periods after each condition.

5.4.8.1 Time Course of Heart Rate

A multifactorial mixed ANOVA revealed a significant effect of BODY, $F(2,1298) = 9.791$, $p < .001$, $\eta_p^2 = .014$, GENDER, $F(1,22) = 10.160$, $p = .004$, $\eta_p^2 = .315$, and TIME, $F(19,1298) = 5.986$, $p < .001$, $\eta_p^2 = .591$, on the HR across time.

There was no significant interaction effect of BODY × GENDER, $F(2,1298) = 2.952$, $p = .052$, $\eta_p^2 = .004$. However, we found a significant interaction effect of GENDER × TIME, $F(19,1298) = 7.814$, $p < .001$, $\eta_p^2 = .102$. Pairwise comparisons using t-tests within BODY showed significant differences between the *non-athletic* and *athletic* ($p < .001$), and the *medium* and *athletic* ($p < .001$) avatars. We did not perform a pairwise cross-factor comparison to further analyze differences between GENDER and TIME, as the interaction did not provide further insights regarding the research question. Additionally, we performed a multivariate linear regression analysis of each subdimension of the BRQ and of the PIS to test whether the variance in HR was affected by the experienced body ownership or identification with the avatars. We found a significant

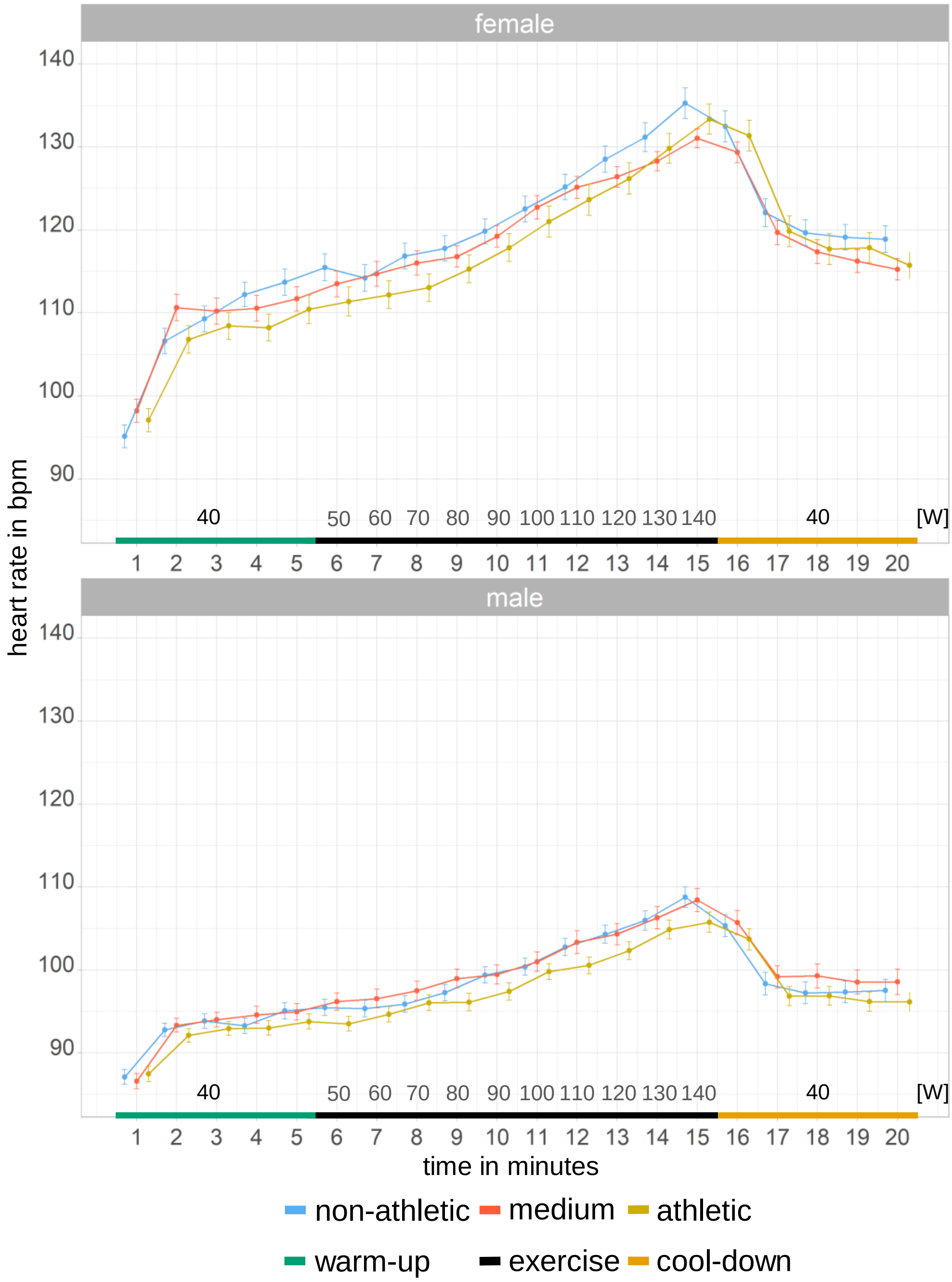

Figure 5.10: Average HR per minute during the warm-up, exercise, and cool-down phase with different workloads in watts [W]. The error bars show the 95% confidence interval.

effect of the subdimensions *vrbody*, $\beta = -2.740$, $p < .001$, *mirror*, $\beta = 4.959$, $p < .001$, *features*, $\beta = -.911$, $p = .008$, and *twobodies*, $\beta = -1.370$, $p < .001$, on participants' HR across time, $F(5,1434) = 38.740$, $p < .001$, $R^2 = .119$, $R^2_{\text{adj}} = .115$. Furthermore, we found a significant effect of the subscale *embodied presence* of the PIS, $\beta = 8.180$, $p < .001$, on participants' HR across time, $F(3,1436) = 75.870$, $p < .001$, $R^2 = .136$, $R^2_{\text{adj}} = .134$. To determine if the participants' BMI had an effect on the HR across time, we performed a mixed analysis of covariance and included the BMI as a covariate. We did not find a significant effect of the BMI, $F(1,21) = 3.405$, $p = .079$, $\eta^2_p = .139$, on the HR across time.

5.4.8.2 Average Heart Rate during Exercise

A multifactorial mixed ANOVA did not find a significant effect of BODY, $F(2,44) = 0.815$, $p = .449$, $\eta^2_p = .035$, however, there was an effect of GENDER, $F(1,22) = 10.140$, $p = .004$, $\eta^2_p = .315$, on the average HR during the exercise. There was no significant interaction effect of BODY × GENDER, $F(2,44) = 0.248$, $p = .782$, $\eta^2_p = .011$.

5.4.8.3 Average Heart Rate during Resting Periods

A multifactorial mixed ANOVA did not find a significant effect of BODY, $F(2,44) = 1.336$, $p = .273$, $\eta^2_p = .057$, of GENDER, $F(1,22) = 2.853$, $p = .105$, $\eta^2_p = .114$, nor an interaction effect of BODY × GENDER, $F(2,44) = 0.251$, $p = .779$, $\eta^2_p = .011$, on the average HR during the resting periods.

5.4.8.4 Perceived Exertion

A multifactorial mixed ANOVA revealed a significant main effect of BODY, $F(2,44) = 55.307$, $p < .001$, $\eta^2_p = .715$, and GENDER, $F(1,22) = 7.712$, $p = .011$, $\eta^2_p = .259$, on the perceived exertion. There was no significant interaction effect of BODY × GENDER, $F(2,44) = 0.827$, $p = .444$, $\eta^2_p = .036$. Pairwise comparisons using t-tests within BODY showed significant differences between all avatars (all $p < .001$). Additionally, we performed a multivariate linear regression analysis of each subdimension of the BRQ and of the PIS to test whether the variance in perceived exertion is affected by the experienced body ownership or identification with the avatars. We found a significant effect of the subdimensions *mirror*, $\beta = .401$, $p = .009$, and *agency*, $\beta = -.482$, $p = .002$, on participants' perceived exertion, $F(5,66) = 4.056$, $p = .002$, $R^2 = .235$, $R^2_{\text{adj}} = .177$.

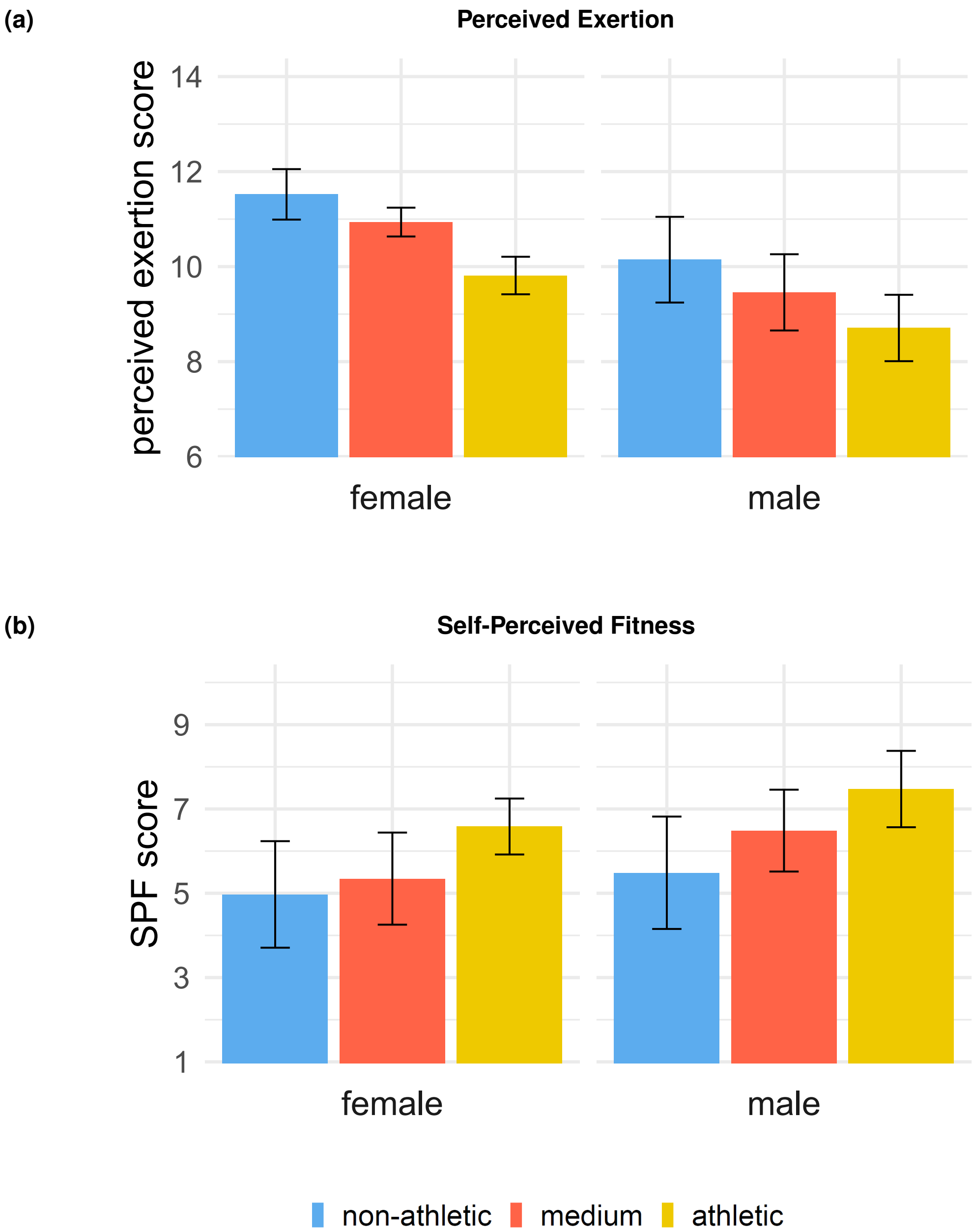

Figure 5.11: Average scores of the perceived exertion while riding the ergometer bicycle ranging from 6 to 20 (a) and the mean values of the SPF questionnaire ranging from 1 to 13 (b). For the sake of clarity, we calculated a total score from the subscales of the SPF questionnaire for this bar chart. The error bars show the 95% confidence interval.

However, we could not find a significant effect of the subscales of the PIS, $p = .340$, on participants' perceived exertion. To determine if the participants' BMI had an effect on the perceived exertion, we performed a mixed analysis of covariance and included the BMI as a covariate. We could not find a significant effect of the BMI, $F(1,21) = 0.782$, $p = .386$, $\eta_p^2 = .035$, on the perceived exertion. Figure 5.11a depicts the mean ratings of the perceived exertion.

5.4.8.5 Time Course of the Pedaling Frequency

We analyzed the time course per minute of the pedaling frequency by including the factor TIME into the statistical analyses. Figure 5.12 shows the time course of the pedaling frequency per minute. We performed a multifactorial mixed ANOVA and found a significant effect of BODY, $F(2,1298) = 7.071$, $p < .001$, $\eta_p^2 = .010$, however, there was no significant effect of GENDER, $F(1,22) = 0.320$, $p = .577$, $\eta_p^2 = .014$, on the pedaling frequency across time. We found a significant effect of TIME, $F(19,1298) = 8.486$, $p < .001$, $\eta_p^2 = .110$, and a significant interaction effect of BODY $\times$ GENDER, $F(2,1298) = 16.537$, $p < .001$, $\eta_p^2 = .002$, and GENDER $\times$ TIME, $F(19,1298) = 1.817$, $p < .016$, $\eta_p^2 = .025$. Subsequent pairwise comparisons using *t*-tests within BODY showed significant differences between the *non-athletic* and *athletic* ($p = .002$), and the *medium* and *athletic* ($p = .027$) avatars.

Pairwise cross-factor comparisons within the *male* avatars revealed a significant effect between the *non-athletic* and *athletic* ($p < .001$), and the *non-athletic* and *medium* ($p < .001$) avatars. Pairwise cross-factor comparisons within the *female* avatars revealed a significant effect between the *non-athletic* and *medium* ($p < .001$), and the *medium* and *athletic* ($p = .001$) avatars. We did not perform further pairwise cross-factor comparisons to analyze differences between GENDER and TIME, as the interaction did not provide further insights regarding the research question. Furthermore, we performed a multivariate linear regression analysis of each subdimension of the BRQ and of the PIS to test whether the variance in the pedaling frequency across time is affected by the experienced body ownership or identification with the avatars. We found a significant effect of the subdimensions *vrbody*, $\beta = 1.401$, $p < .001$, *mirror*, $\beta = -1.158$, $p < .001$, *features*, $\beta = .364$, $p = .033$, *twobodies*, $\beta = 1.204$, $p < .001$, and *agency*, $\beta = -2.756$, $p < .001$, on participants' pedaling frequency across time, $F(5,1434) = 67.460$, $p < .001$, $R^2 = .190$, $R^2_{\text{adj}} = .187$. Furthermore, we could find a

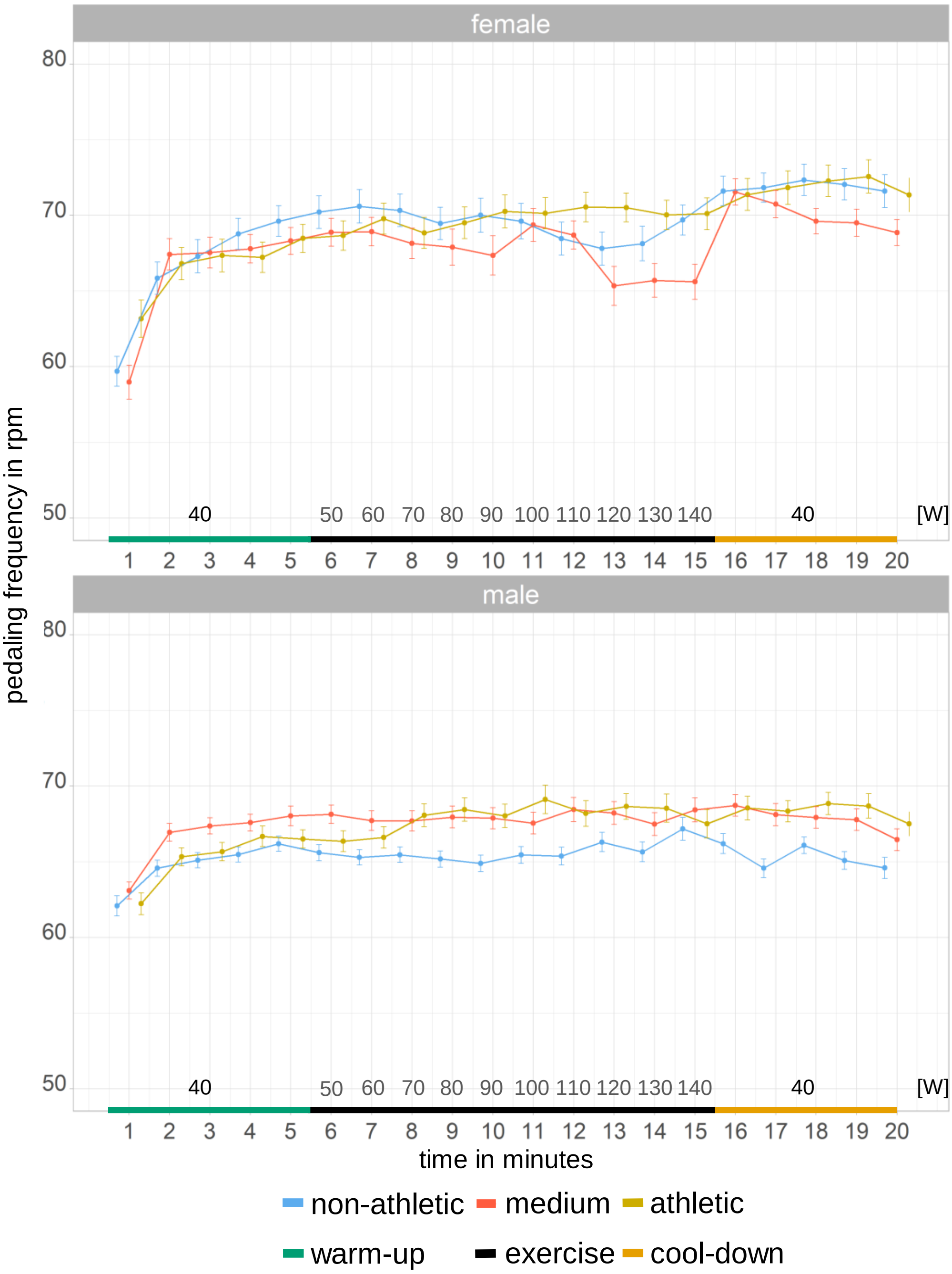

Figure 5.12: Average pedaling frequency per minute during the warm-up, exercise, and cool-down phase with different workloads in watts [W]. The error bars show the 95% confidence interval.

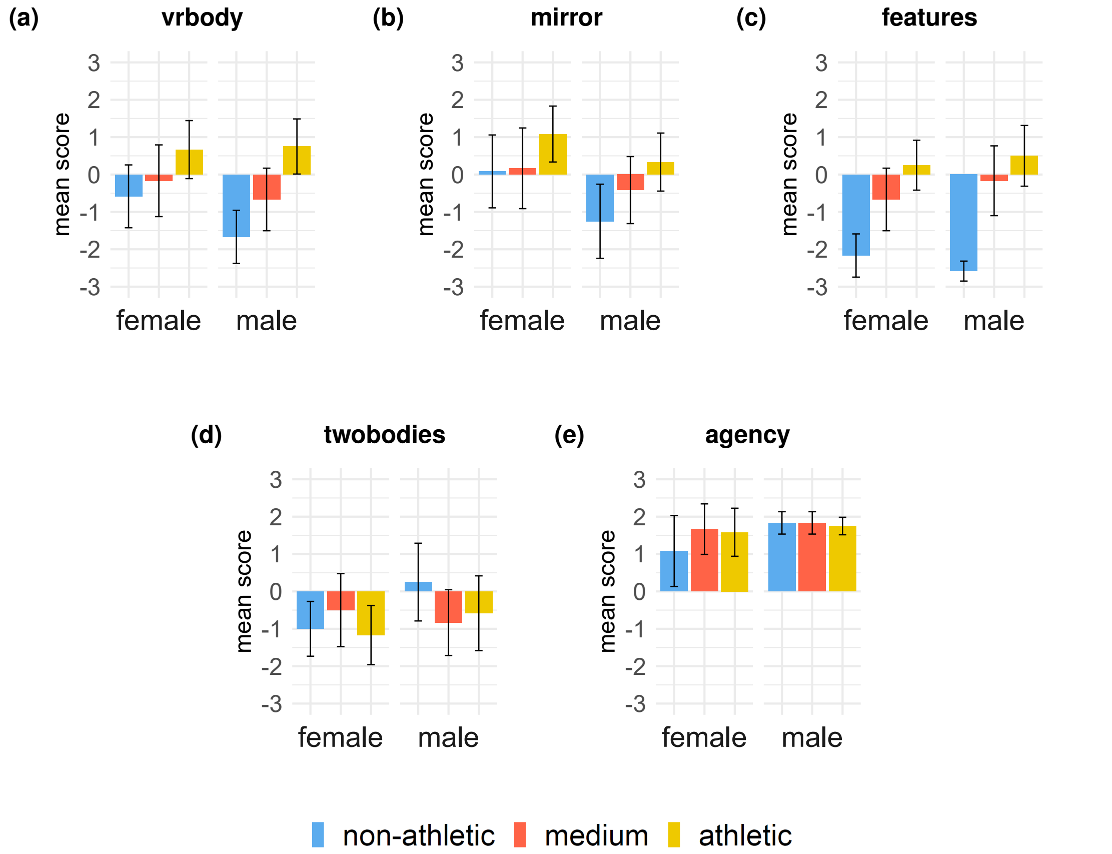

Figure 5.13: BRQ scores on body ownership for each subdimension (vrbody, mirror, features, twobodies, agency). The error bars show the 95% confidence interval.

significant effect of the subscale *embodied presence* of the PIS, $\beta = -.838$, $p < .011$, and *similarity identification*, $\beta = 1.957$, $p < .001$, on participants' pedaling frequency across time, $F(3, 1436) = 10.730$, $p < .001$, $R^2 = .021$, $R^2_{\text{adj}} = .019$.

5.4.8.6 Average Pedaling Frequency

We performed a multifactorial mixed ANOVA and found neither a significant effect of BODY, $F(2, 44) = 0.579$, $p = .565$, $\eta^2_p = .025$, GENDER, $F(1, 22) = 0.319$, $p = .578$, $\eta^2_p = .014$, nor an interaction of BODY $\times$ GENDER, $F(2, 44) = 1.355$, $p = .269$, $\eta^2_p = .058$, on the average pedaling frequency.

5.4.8.7 Distance

To detect significant differences in the covered distance for each avatar condition, we performed a multifactorial mixed ANOVA. We neither found a significant effect of BODY, $F(2,44) = 1.601$, $p = .213$, $\eta_p^2 = .067$, of GENDER, $F(1,22) = 0.328$, $p = .572$, $\eta_p^2 = .014$, nor an interaction effect of BODY × GENDER, $F(2,44) = 2.011$, $p = .146$, $\eta_p^2 = .083$, on the distance covered on the stationary bicycle.

5.4.8.8 Body Ownership

We performed multiple multifactorial mixed ART ANOVAs on each subscale of the BRQ. We found a significant effect of BODY, $F(2,44) = 13.790$, $p < .001$, $\eta_p^2 = .385$, however, there was neither a significant effect of GENDER, $F(1,22) = 1.435$, $p = .243$, $\eta_p^2 = .061$, nor an interaction effect of BODY × GENDER, $F(2,44) = 1.716$, $p = .191$, $\eta_p^2 = .072$, on the subscale *vrbody*. Pairwise comparisons using Wilcoxon signed-rank tests within BODY revealed significant differences between the *non-athletic* and *athletic* ($p = .001$), and *medium* and *athletic* ($p = .049$) avatars.

We found a significant effect of BODY, $F(2,44) = 7.283$, $p = .001$, $\eta_p^2 = .248$, on the subscale *mirror*, however, there was no significant effect of GENDER, $F(1,22) = 3.672$, $p = .068$, $\eta_p^2 = .143$, and no interaction effect BODY × GENDER, $F(2,44) = 1.270$, $p = .290$, $\eta_p^2 = .054$. Pairwise comparisons using Wilcoxon signed-rank tests within BODY showed significant differences between the *non-athletic* and *athletic* ($p = .003$) avatars. Other pairwise comparisons were not significant.

There was a significant effect of BODY, $F(2,44) = 27.433$, $p < .001$, $\eta_p^2 = .554$, on the subscale *features*, however, there was no significant effect of GENDER, $F(1,22) = 0.076$, $p = .784$, $\eta_p^2 = .003$, and no interaction effect BODY × GENDER, $F(2,44) = 1.044$, $p = .360$, $\eta_p^2 = .045$. Pairwise comparisons using Wilcoxon signed-rank tests within BODY showed significant differences between the *non-athletic* and *athletic* ($p < .001$), and *non-athletic* and *medium* ($p < .001$) avatars.

There was neither a significant effect of BODY, $F(2,44) = 1.047$, $p = .359$, $\eta_p^2 = .045$, GENDER, $F(1,22) = 0.757$, $p = .393$, $\eta_p^2 = .033$, nor an interaction effect of BODY × GENDER, $F(2,44) = 2.327$, $p = .109$, $\eta_p^2 = .095$, on the subscale *twobodies*.

There was neither a significant effect of BODY, $F(2,44) = 1.115$, $p = .336$, $\eta_p^2 = .048$, GENDER, $F(1,22) = 1.678$, $p = .208$, $\eta_p^2 = .070$, nor an interaction effect of BODY × GENDER, $F(2,44) = 1.746$, $p = .186$, $\eta_p^2 = .073$, on the subscale *agency*. Figure 5.13 shows the mean ratings for the subdimensions of the BRQ for each condition.

5.4.8.9 Self-Perceived Fitness

We performed multiple mulitfactorial mixed ART ANOVAs on each subscale of the SPF questionnaire to detect differences in the perceived fitness for each avatar. We found a significant effect of BODY, $F(2,44) = 8.581$, $p < .001$, $\eta_p^2 = .280$, however, there was neither a significant effect of GENDER, $F(1,22) = 0.754$, $p = .394$, $\eta_p^2 = .033$, nor an interaction effect of BODY × GENDER, $F(2,44) = 0.512$, $p = .602$, $\eta_p^2 = .022$, on the subscale *fitness*. Pairwise comparisons using Wilcoxon signed-rank test within BODY showed significant effects between the *non-athletic* and *athletic* ($p = .016$), and the *medium* and *athletic* ($p = .020$) avatars.

We found a significant effect of BODY, $F(2,44) = 11.058$, $p < .001$, $\eta_p^2 = .334$, however, there was neither a significant effect of GENDER, $F(1,22) = 2.546$, $p = .124$, $\eta_p^2 = .103$, nor an interaction effect of BODY × GENDER, $F(2,44) = 0.095$, $p = .909$, $\eta_p^2 = .004$, on the subscale *endurance*. Pairwise comparisons using Wilcoxon signed-rank tests within BODY showed significant effects between the *non-athletic* and *athletic* ($p = .003$), the *medium* and *athletic* ($p = .014$), and the *non-athletic* and *medium* ($p = .021$) avatars.

There was a significant effect of BODY, $F(2,44) = 7.862$, $p = .001$, $\eta_p^2 = .263$, however, we did not find a significant effect of GENDER, $F(1,22) = 0.597$, $p = .447$, $\eta_p^2 = .026$, nor an interaction effect of BODY × GENDER, $F(2,44) = 0.190$, $p = .827$, $\eta_p^2 = .008$, on the subscale *flexibility*. Pairwise comparisons using Wilcoxon signed-rank tests within BODY showed significant effects between the *non-athletic* and *athletic* ($p = .021$), and the *medium* and *athletic* ($p = .048$) avatars.

There was a significant effect of BODY, $F(2,44) = 5.583$, $p = .006$, $\eta_p^2 = .202$, and GENDER, $F(1,22) = 5.874$, $p = .024$, $\eta_p^2 = .210$, on the subscale *strength*. We did not find an interaction effect of BODY × GENDER, $F(2,44) = 0.460$, $p = .633$, $\eta_p^2 = .020$. Pairwise comparisons using Wilcoxon signed-rank tests within BODY showed significant effects between the *non-athletic* and *athletic* ($p = .044$) avatars. Other pairwise comparisons were not significant.

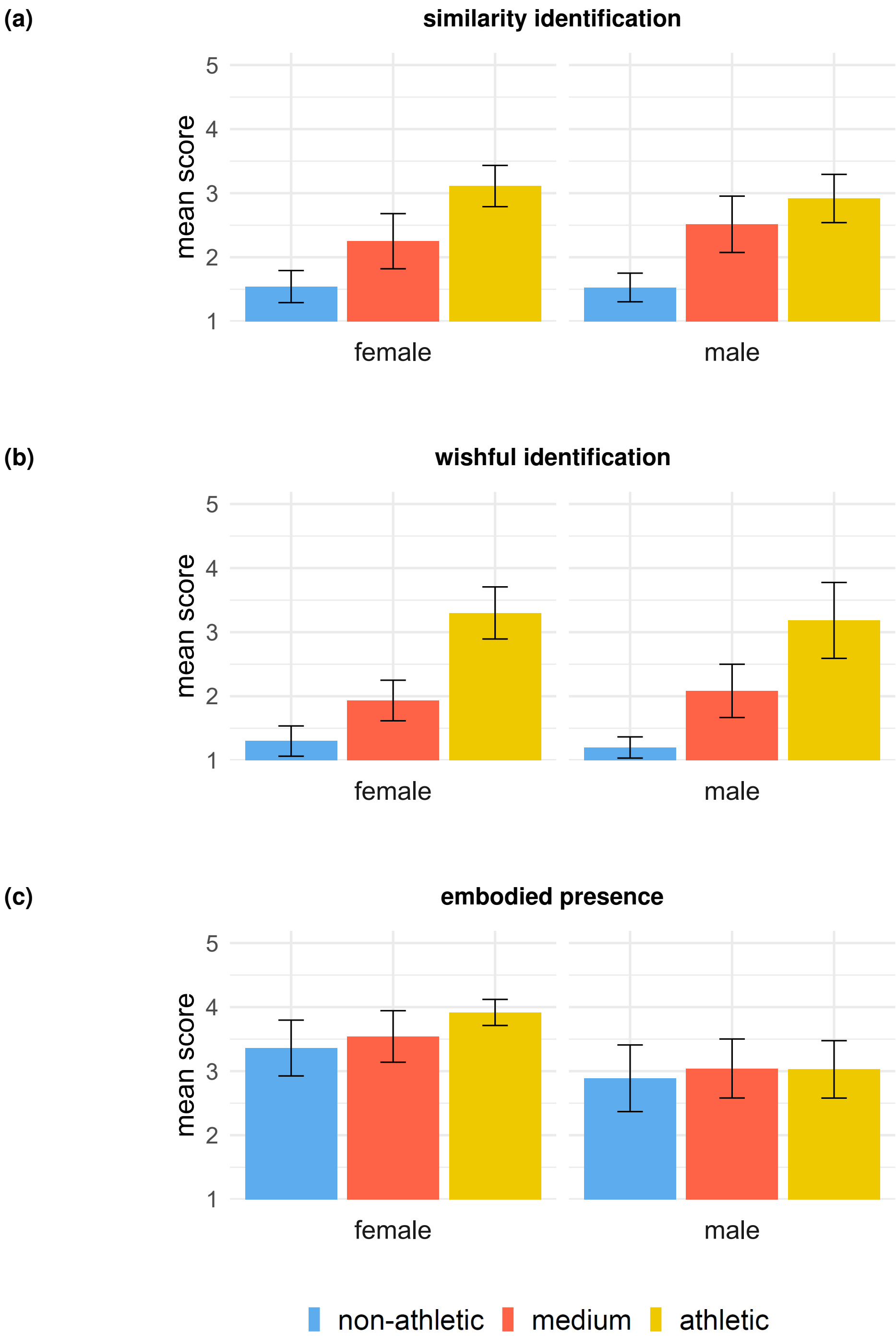

Figure 5.14: PIS scores on user identification for each subdimension (similarity identification, wishful identification, embodied presence). The error bars show the 95% confidence interval.

We found a significant effect of BODY, $F(2,44) = 8.925$, $p < .001$, $\eta_p^2 = .288$, however, there was neither a significant effect of GENDER, $F(1,22) = 2.662$, $p = .116$, $\eta_p^2 = .107$, nor an interaction effect of BODY × GENDER, $F(2,44) = 0.407$, $p = .667$, $\eta_p^2 = .018$, on the subscale *body composition*. Pairwise comparisons using Wilcoxon signed-rank tests within BODY showed significant effects between the *non-athletic* and *athletic* ($p = .017$), and the *medium* and *athletic* ($p = .011$) avatars. Figure 5.11b depicts the mean ratings of the SPF questionnaire.

5.4.8.10 User Identification

We performed multiple mixed ANOVAs on the measures of the PIS consisting of *similarity identification*, *wishful identification*, and *embodied presence*. We found a significant main effect of BODY, $F(2,44) = 42.814$, $p < .001$, $\eta_p^2 = .660$, on *similarity identification*. There was neither a significant effect of GENDER, $F(1,22) = 0.008$, $p = .929$, $\eta_p^2 = .000$, nor an interaction effect of BODY × GENDER, $F(2,44) = 1.036$, $p = .363$, $\eta_p^2 = .044$. Pairwise comparisons using t-tests within BODY showed significant differences between the *non-athletic* and *athletic* ($p < .001$), the *medium* and *athletic* ($p = .005$), and the *non-athletic* and *medium* ($p < .001$) avatars.

We found a significant main effect of BODY, $F(2,44) = 70.192$, $p < .001$, $\eta_p^2 = .761$, on *wishful identification*. There was neither a significant effect of GENDER, $F(1,22) = 0.010$, $p = .923$, $\eta_p^2 = .000$, nor an interaction effect of BODY × GENDER, $F(2,44) = 0.338$, $p = .681$, $\eta_p^2 = .017$. Pairwise comparisons using t-tests within BODY showed significant differences between all avatars (all $p < .001$).

There was no significant effect of BODY, $F(2,44) = 2.530$, $p = .091$, $\eta_p^2 = .103$, however, we found a significant effect of GENDER, $F(1,22) = 4.845$, $p = .038$, $\eta_p^2 = .180$. There was no significant interaction effect of BODY × GENDER, $F(2,44) = 1.138$, $p = .329$, $\eta_p^2 = .049$, on *embodied presence*. Figure 5.14 depicts the PIS ratings for each condition.

5.4.9 Discussion

The effects of the avatars' athleticism on perceived exertion replicate our previous findings on the Proteus effect during physical tasks in VR (see Section 5.3; Kocur et al., 2020c). We found a systematic relationship between the users' perception of effort and the avatar's athletic appearance. The analysis of quantitative data also shows that the participants' HR was significantly lower when embodying the athletic avatar compared to the non-athletic and medium avatar. These results imply that the avatar's appearance does not only affect the users' perceived exertion but can also influence their HR while cycling in VR. We dismiss effects of fatigue as an explanation for the variance in HR between the avatars since we adhered to a standardized protocol (Northridge et al., 1990) to ensure that the participants had an identical workload per avatar condition within the aerobic threshold of 75% of the maximum HR (Park et al., 2014).

5.4.9.1 Perception of Effort

Overall, these findings are consistent with the notion that an avatar's appearance representing certain traits can affect the users' performance during tasks that are in turn concomitant with the attributes of the virtual avatar. By inducing a feeling of owning a virtual body with a high level of athleticism, the users adopt the salient characteristics of the avatar and integrate them into their mental representation of the new self during exposition in VR. In line with self-perception theory (Bem, 1972), the users, therefore, attribute the avatars' characteristics to themselves and adhere to their new virtual identity. Hence, a perception-behavior process (Chartrand & Bargh, 1999) is triggered so that the activated associations of athletic people performing well at physical exercises prime the users and, accordingly, affect their perception of effort.

The finding that an avatar's athletic appearance can potentially decrease the perceived exertion while performing physically demanding tasks is important and promising for designers and developers of VR exercise systems. It shows the potential of certain avatars to make users perceive vigorous exercise as less physically intense and exhaustive. Prior research in the field of exercise science showed that the perception of effort is a key factor of the psychobiological model which describes the regulation of human behavior during physical exertion (Pageaux, 2014). The psychobiological model states that when a person's perception of effort is increased or decreased, the person will accordingly adapt the pace to compensate for the effects. Therefore, a higher perception of effort can limit endurance performance as we faster reach the maximum amount of effort we are willing to exert (Marcora & Staiano, 2010). Similar applies to engagement and adherence to physical activities as a higher perception of effort reduces the exercise tolerance—the capacity to sustain physical exercise (Pageaux, 2014). As the perception of effort can be a barrier to regular physical activity and contributes to exercise adherence (Marcora, 2016; Bauman et al., 2012), its reduction using avatars in VR exercises may, therefore, pose an opportunity to engage users and incentivize physical activity. This is in line with an editorial by Marcora (2016) who debates the use of psychoactive drugs such as caffeine, which can reduce the perception of effort and unpleasant sensations during intense exercise to foster adherence to this kind of exercise.

5.4.9.2 Effects on Heart Rate

To explain the effect of a decreased HR when embodying the athletic avatar while cycling in VR, we refer to research in sports psychology that has shown different psychophysiological effects on professional and amateur athletes during exercise, for example, caused by high-fives (Lautenbach et al., 2019), exercise in a group (Vandoni et al., 2016), music (Lim et al., 2014; Bigliassi, 2018; Brownley et al., 1995; Patania et al., 2020), television (Rider et al., 2016), biofeedback training (Goldstein et al., 1977), as well as mental imagery (Hecker & Kaczor, 1988). In sports psychology, mental imagery has proven to be an effective psychological tool to improve physical performance (Slimani & Chéour, 2016; Wang & Morgan, 1992; McCormick et al., 2015) and describes the self-visualization while exercising, e.g., visualizing oneself being motivated and engaged or with an enhanced physical appearance (Razon et al., 2014). Transferring this idea to virtual avatars, VR supports the mental imagery process by vividly visualizing what it would be like to own a body with different degrees of athleticism during the actual exertion. As shown in the SPF scores, the participants attributed a high level of fitness and athleticism to the athletic avatars.

Since self-confidence and self-efficacy were identified as one of the underlying mechanisms for the induced changes in physical performance and physiological responses through mental imagination (Slimani et al., 2016), we hypothesize that the participants felt more confident in the athletic than in the medium and non-athletic avatar to be able to master the upcoming challenge and to perform well. This could, in turn, result in a lower stress level indicated by a decreased HR. Future investigations are needed to verify our assumption by assessing the participants' confidence and self-efficacy as well as the degree of excitement during virtual embodiment. Furthermore, a visual comparison of the average HR across time suggests that the athletic avatars' impact remained stable throughout the warm-up and exercise, but decreases during cool-down. Hence, future studies should focus on the time course of the Proteus effect and how this phenomenon evolves over time to understand how to harness the full potential of the effect.

Research in psychology also offers the attentional shift (Lind et al., 2009) caused by the avatars' appearances as a potential explanation for the effects found in our study. Bigliassi et al. (2016) showed, for example, that motivational audiovisual stimuli could affect the brain activity resulting in a decreased feeling of fatigue in the muscles. Researchers agree that a shift in attention from internal cues, e.g., HR or fatigue, to external cues, e.g., music or video, influences physiological responses to physical activity, e.g., attenuating stress and arousal (Rejeski, 1985; Rider et al., 2016). Although we did not specifically assess attention in terms of association and dissociation (Lind et al., 2009), the virtual body itself provided the main cues that could have been the focus of users' attention.

Considering the scores of the BRQ and the PIS, we induced the strongest body ownership in the athletic avatars with the highest score for similarity identification, indicating that the avatars with an athletic appearance are most akin to the participants' physical body. The aforementioned theory of shifting attention would suggest that participants were distracted by the avatars with features and characteristics that deviated from their real physical body, potentially attenuating physiological responses such as the HR, which was not the case. We, however, found that participants had a lower HR in the avatar with an athletic appearance, that is why we assume that the shift in attention is not the driver for a decrease in the HR. To validate our assumption, future work could include measures of assessing the participants' attentional focus while embodying virtual avatars with different attributes during physical exertion.

5.4.9.3 Pedaling Frequency

The Proteus effect suggests that the participants behave in accordance with the common expectations connected with the avatars' appearance. One might assume that the elicited behavioral changes due to the embodiment of the avatars affect the physiological responses while cycling in VR. Although we found changes in behavior with regard to the pedaling frequency induced by the avatars' athleticism, they cannot explain the differences in HR as there is no systematic effect of the athletic avatars that are in line with the HR across time. These unsystematic behavioral correlates support previous work showing that idealized avatars can either enhance or decrease the power output while cycling in a competitive VR exergame (Koulouris et al., 2020). This is also in line with Peña and Kim (2014) who showed that players of a tennis exergame can exhibit a decreased physical activity when they think that their avatar has either a physical advantage or a disadvantage over the opponents' virtual character. Hence, more research is needed to understand behavioral changes caused by an avatar's appearance in a sports context due to these ambiguous findings.

5.4.9.4 Body Ownership and BMI

We also found a relationship between the body ownership ratings and the perception of effort, the HR across time, and the pedaling frequency. Additionally, there were correlations between the subscales of the user identification and the HR across time as well as the pedal frequency. Hence, we cannot rule out effects of the experienced body ownership and the identification with the avatars on physiological responses and behavioral changes. Considering the ratings of the BRQ, which were generally low for the male- and female-gendered non-athletic and medium avatars, the extent of the body ownership may partially explain the effects on the perception of effort and HR response. This is supported by findings from prior investigations showing that a user's physiological behavior is affected by the degree of full-body ownership of virtual avatars.

Slater et al. (2010), for example, found in a VR experiment that participants who embodied an avatar from a third-person perspective had a lower HR in response to a virtual threat compared to when embodying an avatar from a first-person perspective. Likewise, Bergström et al. (2016) demonstrated that the HR and HR variability correlates with the strength of the experienced body ownership. The authors found that an uncomfortable body posture of an avatar increases the HR and that the rise in HR is associated with a higher level of body ownership. Due to these findings, we cannot conclude that the effects arose as a function of the avatars' appearance. Additionally, previous work found that avatars with characteristics fundamentally different than one's own physical body can provide a novel experience increasing excitement and interest (Banakou et al., 2018; Krekhov et al., 2019b). Therefore, the non-athletic and medium avatar could trigger engagement and excitement resulting in arousal which raised the HR.

Our results did not determine if the non-athletic and medium avatar increased or the athletic avatar decreased the HR. Consequently, more research is needed to explore the relationship between avatars which are associated with a high level of fitness, and the induced physiological changes. As research suggests that body ownership is a significant moderator of the Proteus effect (Banakou et al., 2013), future work should aim to design appropriate avatars with characteristics representing the desired degrees of physical fitness without deteriorating the body ownership and agency. We hypothesize that such avatars can be achieved by enabling the users to customize the avatars' appearance during embodiment in VR based on predefined requirements.

We assume that a user's physical condition could also mediate the Proteus effect during exercise in VR. We analyzed the BMI as a potential moderator by including it as a covariate in our statistical analyses. However, we could not find any effects indicating a relationship between the psychophysiological effects of an avatar's appearance and the participant's BMI. This can be because our participants had similar BMIs ($M = 22.74$, $SD = 2.61$). Nonetheless, we do not rule out that a user's physical condition and fitness mediates the Proteus effect during physical activity. Since we did not systematically control the BMI in our study, future work should investigate whether and to what extent one's physical condition and athleticism mediate avatars' effects during physical effort.

5.4.9.5 Adverse Effects and Risks

Regardless of whether the effects are caused by the extent of the perceived body ownership or the avatar's athletic appearance, the psychophysiological impact of avatars on users during physical exertion should be considered when designing avatars for VR exercise systems. As the perception of effort and HR are variables that represent the psychological and physiological response to physical effort, their manipulation can entail risks. Iodice et al. (2019), for example, provided false acoustic HR feedback during cycling in a real-world experiment to modulate the perception of effort. Similar to an exteroceptive BOI as a misperception of a brain's body representation, the authors, therefore, induced an interoceptive illusion—a misperception of one's physiological state in terms of effort. The authors found that an increased HR feedback caused a higher perception of effort so that the participants overestimated their perceived exertion.

Interestingly, a decreased HR feedback did not result in a lower perception of effort. They argued that this asymmetry is due to a cautious risk-averse strategy, as underestimating the perceived exertion may mislead someone to exercise with an intensity that exceeds one's physical ability. Hence, inappropriate exercise intensities can, for example, increase the risk for injuries (Rynecki et al., 2019), sore muscles (Clarkson & Newham, 1995), overexertion (Lind et al., 2009), and reduce exercise adherence (Rhea et al., 2009; Rynecki et al., 2019; Lee et al., 2016). We, however, found a decreased perception of effort with a lower HR potentially due to the embodiment of an athletic avatar. Although the ratings of the RPE scale indicated that the perceived exertion was generally low with only a slight decrease in HR, the same exercise was perceived as less physically intense when embodied in an avatar whose appearance is connected with better physical abilities compared to the other avatars. Even if our findings seem promising to positively affect the user, the aforementioned adverse effects have to be kept in mind in the avatar creation process particularly regarding beginners of fitness programs and amateur athletes (Gray & Finch, 2015). Consequently, our results need further investigation with a more diverse population considering potential negative effects caused by the embodiment of avatars to better understand the Proteus effect and, therefore, to gain knowledge that contributes to more effective and particularly advantageous usage of avatars in VR exercise applications.

5.4.10 Conclusion

In this section, we investigated the effects of an avatar's athletic appearance on the user's perception of effort and physiological response during physical activity. First, we systematically designed 32 avatars and conducted an initial study to determine the stimuli for our VR experiment. Afterward, we conducted a study with 24 participants who embodied three avatars with different levels of athleticism while riding a stationary bicycle in VR. We found that the participants had a lower HR when embodying the athletic avatars compared to the non-athletic and medium avatars. We also observed a systematic relationship between an avatar's athletic appearance and the perception of effort. Participants embodied in the athletic avatars perceived the exercise as less physically strenuous than embodied in the non-athletic and medium avatars. Our results suggest that avatars that are associated with a high level of fitness can reduce a user's perception of effort and decrease the HR during physical activity in VR. While previous work showed that an avatar's appearance could positively affect physical performance, we found that avatars can even affect physiological responses to effort.

In line with related theories from sports psychology, we assume a boost in confidence due to the athletic avatars resulting in a decreased HR. These findings suggest that avatars may be a powerful tool to positively influence users during physical exertion. More research in a more controlled environment with a larger body of participants is required to confirm our findings, as they may pose a promising opportunity for designers and developers of VR exercise systems to make users perceive high-intensity exercises less physically strenuous, and, therefore, promote physical activity and foster exercise adherence. Future studies can build upon our work to explore the psychophysiological impact of avatars to gain a deeper understanding of the mechanisms underlying exercise performance in VR.

5.5 Summary

In two studies, we showed that the embodiment of avatars associated with high physical abilities can improve physical performance in VR. We found that muscular avatars can increase users' grip strength and decrease the perception of effort while holding weights (see Section 5.3). We also found that athletic avatars can decrease the perception of effort and the HR while cycling in VR (see Section 5.4). Both studies demonstrate that users conform to the avatars' appearance and act and behave as they expect persons with such characteristics would behave in such scenarios. Hence, we argue that they consciously or unconsciously adapted the physical effort they put into the tasks based on the avatar and its expected abilities. Furthermore, our results indicate that avatars with attributes deviating from the users' real ones affect body ownership and user identification. As we found that body ownership can moderate the effects on physical performance, it is therefore important to induce ownership of avatars to maximize their impact on users.

For this reason, we recommend evaluating the avatars' appearance to assess how (potential) users perceive the stereotypical characteristics before usage in VR applications. We, therefore, conducted an online survey using renderings of avatars with different degrees of athleticism (see Section 5.4.2). Hence, we aimed to ensure that the used avatars activate the intended stereotypical concepts such as high physical abilities without deteriorating the experienced body ownership and dissociating users from the avatars. Overall, the results imply that designers and researchers of VR exercise systems can leverage the avatars' appearance to positively affect users' performance, perception of effort, and physiological responses during physical exercise in VR.

6

Improving Cognitive Performance

In the previous chapter, we found that the embodiment of avatars representing characteristics that are associated with high physical abilities can improve performance in physical tasks. In this chapter, we focus on the cognitive performance while being immersed in VR to learn whether such effects also translate to other settings. As theories from social psychology (e.g, behavioral confirmation; Snyder et al., 1977) suggest that one's behavior also depends on the perception and behavior of others, we also explored whether and how the Proteus effect operates in a CVE with co-located users. We could not find the Proteus effect in terms of increased cognitive performance while embodying Albert Einstein. However, we found that the other users who shared the same virtual space with an Einstein avatar performed better at a cognitively demanding task. Our work suggests that social interaction can decrease or even extinguish the Proteus effect. Hence, the avatars' visual appearance to both, the user and the others must be considered when designing CVEs due to the interpersonal perception of multiple users.

This chapter is based on the following publication:

Kocur, M., Schauhuber, P., Schwind, V., Wolff, C., & Henze, N. (2020e). "The Effects of Self- and External Perception of Avatars on Cognitive Task Performance in Virtual Reality." In: *26th ACM Symposium on Virtual Reality Software and Technology*. VRST '20. Virtual Event, Canada: Association for Computing Machinery, pp. 1–11. ISBN: 9781450376198. DOI: 10.1145/3385956.3418969.

6.1 Collaborative Virtual Environments

Due to the progress of VR technology, VEs has evolved into CVEs where multiple users share the same virtual space regardless of their actual physical location. Nowadays, millions of users play and interact with each other in large-scale online games via avatars (Chan & Vorderer, 2006). In such CVEs users' behavior is affected by the behavior of other users. This type of social interaction is described by the behavioral confirmation paradigm that predicts that a person's behavior depends on self-perception and the perception by others (Snyder et al., 1977). Snyder et al. (1977) revealed the effect in a study conducted in the real world investigating communication behavior during a telephone call. Male participants (referred to as perceivers) who believed that the female counterpart (referred to as the target) was attractive caused her to behave more friendly and likable compared to targets whom perceivers believed to be unattractive. Results indicate that the perception of others defines and affects our behavior. Hence, behavioral changes due to one's avatar should also be considered in the context of others' perception. The reciprocal influence of perceivers' and targets' beliefs and expectations associated with the visual appearance of the avatars evoke behavioral changes. As prior research investigated behavioral changes caused by the avatar isolated from effects caused by the behavioral confirmation paradigm, it is unknown whether and how self- and external perception affect users' behavior.

6.2 Method

Previous work found that embodying an avatar that is associated with superior intelligence, e.g., Albert Einstein, affects cognitive task performance after the exposition in VR (Banakou et al., 2018). However, it is unknown to what degree the Einstein avatar influences the behavior and cognition of other users in CVEs. It is important for the design of CVEs in general and virtual characters, in particular, to understand how the visual appearance of an avatar affects the behavior and VR experience of one's self and the other users. Thus, we investigate whether and how the embodiment of Einstein influences the performance in a cognitively demanding Tower of London (TOL) task (Shallice, 1982) performed within a CVE when a user's self-perception and external perception differ. The effects on the perceived task load, the sense of presence, social presence as well as body ownership were assessed.

6.2.1 Study Design

We selected the stimuli based on previous work by Banakou et al. (2018) to investigate the effects of users' self- and external perception on their cognitive task performance. We conducted a mixed-design study with two independent variables. Two participants were simultaneously in the same VE. In line with behavioral confirmation theory (Snyder et al., 1977), we considered their roles as *target* or *perceiver*. One participant was the *target* whereas the other was the *perceiver*. The only between-subject variable was the target's SELF-PERCEPTION with the two levels being *Einstein* or being a *Normal* avatar. Thus, the targets embodied either Einstein or a normal avatar.

To assess how the perception of the other participant affects cognitive performance, we used the EXTERNAL PERCEPTION as within-subjects variable with the two levels as *Seeing Einstein* or *Seeing a Normal* avatar. The perceivers embodied a normal avatar and saw the target either as Einstein or a normal avatar. The targets were unaware of what the perceivers saw. Since we assumed that a cognitively demanding task can benefit from collaboration, we measured cognitive task performance in a classical TOL solo task as well as in a cooperative task. In the solo task, both participants simultaneously performed a TOL task next to each other. They were not aware of the other's score and game state. In the cooperative task, the two participants played the TOL together on the same board. To reduce the frequency of swapping the avatars, participants performed both TOL tasks (solo and cooperative) consecutively. After completing both tasks, we changed the EXTERNAL PERCEPTION of the perceiver. We counterbalanced the conditions to reduce order effects.

6.2.2 Participants

In line with Banakou et al. (2018) we recruited 32 male participants to avoid gender mismatches between participant and avatar (Schwind et al., 2017b). The recruitment was done through our institution's mailing lists. On average, participants were 25.65 years old ($SD = 4.53$) ranging from 20 to 41 years. All of them had a technical background in computer science or engineering. Participants were compensated with credit points for their study course. We had 29 right-handed and three left-handed participants in our study. All of them had light skin tones matching the visual appearance of the avatars. None of the participants have taken part in a TOL experiment before. All of them had

Figure 6.1: Participants in the real world (top) wearing motion capturing suits and their avatars in VR (bottom) performing the solo TOL task (left) and the cooperative TOL task (right).

either normal or corrected-to-normal vision. We had no dropouts in the study. This study received ethics clearance according to the ethics and privacy regulations of our institution and, thus, follow the policies of our country and funding body.

6.2.3 Apparatus

To immerse participants in a high-fidelity environment, we developed an apparatus that tracks their motions using a full-body motion capture system and renders the scene using a state-of-the-art 3D engine. We implemented the VR application using the Unity3D game engine (v. 2018.3.2f1). As the study required a multi-user setup, the application ran on two identical PCs with Windows 10, Intel i7-8750H, 16GB RAM, and an NVIDIA GeForce GTX 1060 graphics card. We set the target frame rate to 90 FPS on both PCs to ensure a constant frame rate for both participants. We used two HTC Vive HMDs with HTC wireless adapters.

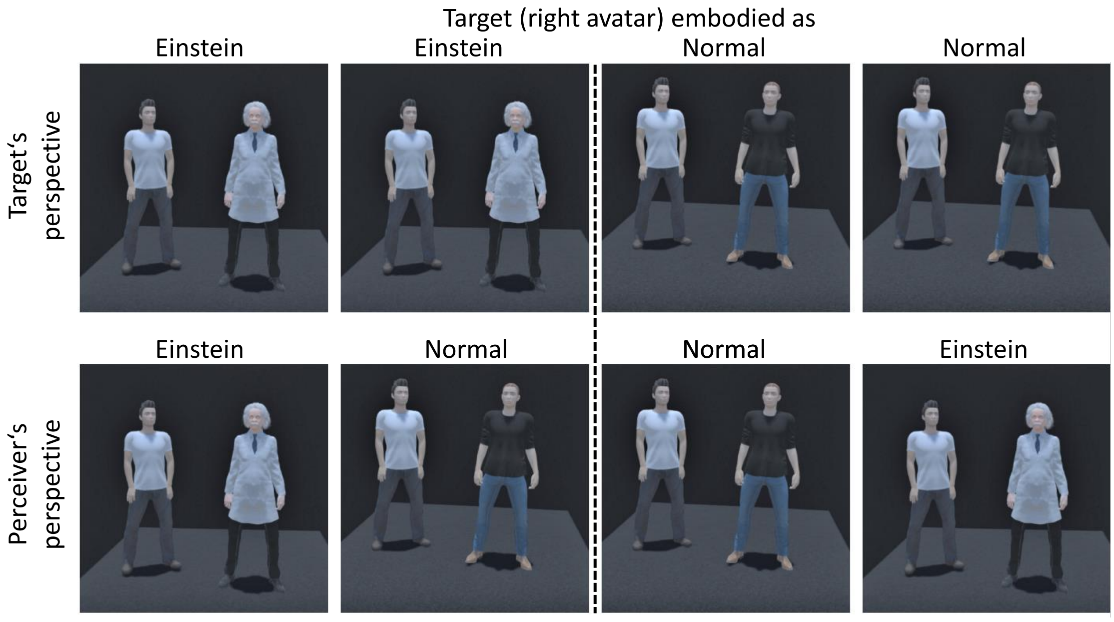

Figure 6.2: The perception of the scene from the target's perspective (top) and the perceiver's perspective (bottom) in each condition. In one group (left of the dotted line), the target was embodied as Einstein and perceived as Einstein, and the target was embodied as Einstein and perceived as normal. In the other group (right of the dotted line), the target was embodied as normal and perceived as normal, and the target was embodied as normal and perceived as Einstein (from left to right).

We designed a simple virtual scene consisting of a room with dark walls, a virtual mirror, questionnaires, and a TOL board. We integrated a virtual mirror into the scene to ensure that the participants could see themselves in the avatars' bodies (see Figure 6.1). Hence, we limited technical factors causing VR sickness through constant visuo-motor synchrony. We created three avatars using the 3D-suite Daz3D. We used the character Genesis 8 for the normal avatars and Floyd 8[1] for the Einstein avatar and adapted their appearance (body shape, facial expressions, skin) by morph targets and textures. To track participants' full-body motion with high accuracy and low latency, we used an OptiTrack motion tracking system with twelve cameras (eight PRIME 13 and four PRIME 13W) and the software Motive (v. 2.1).

The motion tracking software ran on a dedicated PC with Windows 10, Intel i7-8700, 26GB RAM, and an NVIDIA GeForce GTX 1080 graphics card. We calibrated

[1] `https://www.daz3d.com/floyd-8-pro-bundle`

Figure 6.3: The model of the questionnaires in VR.

the OptiTrack system according to the manufacturer's specification and achieved an exceptionally precise calibration result (overall reprojection mean 3D error: 0.852 mm, triangulation residual mean error: 0.8 mm, overall wand mean error: 0.187 mm, worst camera mean 3D error: 0.949 mm). The system tracked the participants while wearing motion capturing suits. We provided suits in different sizes ($2\times$S, $2\times$M, and $2\times$L) with 49 optical markers attached in a given pattern. The OptiTrack system tracked participants' skeleton with 240 FPS. The skeletons were transmitted through a local 1000 Mbit network connection to the two PCs rendering the 3D scene using UDP multicast.

6.2.4 Measures

We took one objective and several subjective measures to determine the effects of the independent variables. We used the score computed when performing the TOL task to measure objective cognitive performance. Participants were asked to fill a raw NASA-Task Load Index (NASA-TLX; Hart & Staveland, 1988; Hart, 2006) for the solo task and an extended version of the NASA-TLX (in the following referred to as the TLX Team) to measure perceived task load of a team for the cooperative task (Savchenko et al., 2019). We determined participants' sense of presence using the IPQ (Schubert et al., 2001), their sense of social presence using the social presence questionnaire (Poeschl & Doering, 2015), and quantified the experience of body ownership using the BRQ (Banakou et al., 2018). In line with Schwind et al. (2019), all questionnaires were filled in the VR environment (see Figure 6.3). Participants filled in the IPQ, the BRQ, and the social presence questionnaire after completing both TOL tasks.

Tower of London Score

The TOL score was used to assess cognitive task performance. Originally defined to detect cognitive impairments, the TOL is a neuropsychological test to assess executive functioning, planning, and problem-solving skills (Shallice, 1982). The TOL task was implemented as suggested by Krikorian et al. (1994).

In the solo task, each participant simultaneously played the TOL alone on a virtual board. In the cooperative task, participants shared one virtual TOL board and performed the task together (see Figure 6.1). The TOL board consisted of three rods in descending heights from left to right and three different bricks colored in blue, red, and green. The heights of the rod indicate the maximum number of bricks allowed to be placed on a rod (left rod: 3, middle rod: 2, right rod: 1). From a predefined starting position participants were asked to strategically move the bricks from one rod to another to match a given pattern. The pattern was shown in the upper part of the TOL board. To complete the TOL task participants had to solve 12 problems with different difficulties depending on the number of allowed moves per problem. The first two problems allow two moves, problems 3 and 4 allow three moves, problems 5 to 8 allow four moves, and problems 9 to 12 allow five moves for solving. A problem is solved when the bricks are arranged in the given order within the prescribed number of moves. Participants had a maximum of three attempts to solve a problem.

The TOL score was calculated according to the algorithm provided by Krikorian et al. (1994). The participants received three points for solving a problem in the first attempt, two points in the second attempt, one point in the third attempt, and zero points if they failed to solve the problem three times. Hence, the maximum score that can be achieved is 36 (solving all of the 12 problems in the first attempt).

6.2.5 Procedure

As participants experienced the VR environment in pairs, we invited them to different rooms in our lab to ensure that they do not meet each other before entering the VR scene. To avoid that the perceiver informed the target about his visual appearance and to prevent mismatches between the appearance of the Einstein avatar and the target's voice, we asked the participants not to speak during the experiment. Hence, there was no conversation between the target and the perceiver before and during the experiment. After welcoming the participants individually, we explained the course of the study. We provided a brief introduction into VR, asked them to sign an informed consent form, and to fill a demographic questionnaire. To familiarize participants with the TOL task, we included a short training phase where they performed the task on a standard desktop computer using a mouse before entering the VR scene. In line with Lazar et al. (2017), we also tried to reduce the impact of learning effects with this training phase, since users learn the most in the initial stages with a lesser improvement in subsequent trials.

After participants felt confident to perform the TOL task, we helped them to put on the motion capture suit and attached 49 markers to track their skeleton. We further explained that while in VR, they can interact with the TOL task and the questionnaires using their hands instead of a mouse. Before leading them into the VR lab, we adjusted the HMDs to the participants' head and calibrated their interpupillary distance for best visual results. After putting on the HMD, we guided both participants into the VR lab where they entered the designed scene. We highlighted that participants could withdraw or discontinue participation at any time without penalty or losing their compensation.

Before participants entered the VR scene, we adjusted the external and internal perception of both participants according to the respective condition. After entering the scene, participants (virtually) met for the first time. To accustom themselves to the VR environment, to perceive their avatar, and to perceive the other participant's avatar, they waited in the VR scene for 30 seconds. Afterward, participants were asked to perform the TOL task as fast and precisely as possible. After completing the TOL task, we asked them to fill in the NASA-TLX. They continued with the cooperative TOL task which was again followed by the NASA-TLX and TLX Team, IPQ, social presence questionnaire, and BRQ.

After completing both tasks and filling all questionnaires, the whole scene faded to black for one second and we adjusted participants' self- and external perception to the next condition. We counterbalanced the order of the conditions in a 4×4 Latin square design. To reduce the frequency of swapping the avatars, participants performed both TOL tasks (solo and cooperative) consecutively. After completing both tasks, we changed the EXTERNAL PERCEPTION of the perceiver (see Figure 6.2). At the end of the study, participants were asked to give feedback about the overall experience, the avatars in VR, and their physical and mental well-being in a brief questionnaire. On average, the study took 75 minutes per participant in total.

6.3 Results

Our measures include both parametric as well as non-parametric data. Shapiro-Wilk tests for normality indicate that the assumption of normal distribution has been violated for scores of the TOL task and of social presence. Items of the BRQ concern ordinal data. For multiple factor analyses of non-parametric data, we used the ARTool package for R by Wobbrock et al. (2011) for hypothesis testing. We performed a multifactorial mixed-design ANOVA on parametric data. Participation was entered as a random factor in all analyses. To ensure that the TCT is not a confounder, we tested the effects of both EXTERNAL PERCEPTION as well as SELF-PERCEPTION on the duration of the TOL tasks and found no statistically significant effects (all $p > .274$). The following results are structured according to whether the measurements were taken from the perceiver or the target.

6.3.1 Perceiver

6.3.1.1 Solo TOL Scores

We found a significant main effect of EXTERNAL PERCEPTION, $F(1,14) = 6.429$, $p = .024$, $\eta_p^2 = .314$, however, not of SELF-PERCEPTION, $F(1,14) = 2.837$, $p = .115$, $\eta_p^2 = .168$, and no interaction effect of EXTERNAL PERCEPTION × SELF-PERCEPTION $F(1,14) = 2.168$, $p = .163$, $\eta_p^2 = .134$, on the TOL score. Thus, the perceivers' performance during the solo task depended on the targets' avatar. When the perceivers saw the target as Einstein, their TOL scores significantly increased (see Figure 6.4a).

6.3.1.2 Cooperative TOL Scores

We found no significant main effects of EXTERNAL PERCEPTION, $F(1,14) = 0.022$, $p = .885$, $\eta_p^2 = .001$, and SELF-PERCEPTION, $F(1,14) = 0.191$, $p = .669$, $\eta_p^2 = .013$, and no interaction effect of EXTERNAL PERCEPTION × SELF-PERCEPTION, $F(1,14) = 0.047$, $p = .832$, $\eta_p^2 = .003$, on the TOL score. Thus, the perceivers' TOL scores during the cooperative tasks were neither affected by the target's avatar nor by how the targets saw themselves (see Figure 6.4b).

6.3.1.3 Solo NASA-TLX Scores

We found no significant main effect of EXTERNAL PERCEPTION, $F(1,14) = 0.101$, $p = .755$, $\eta_p^2 = .007$, however, we found a significant effect of SELF-PERCEPTION,

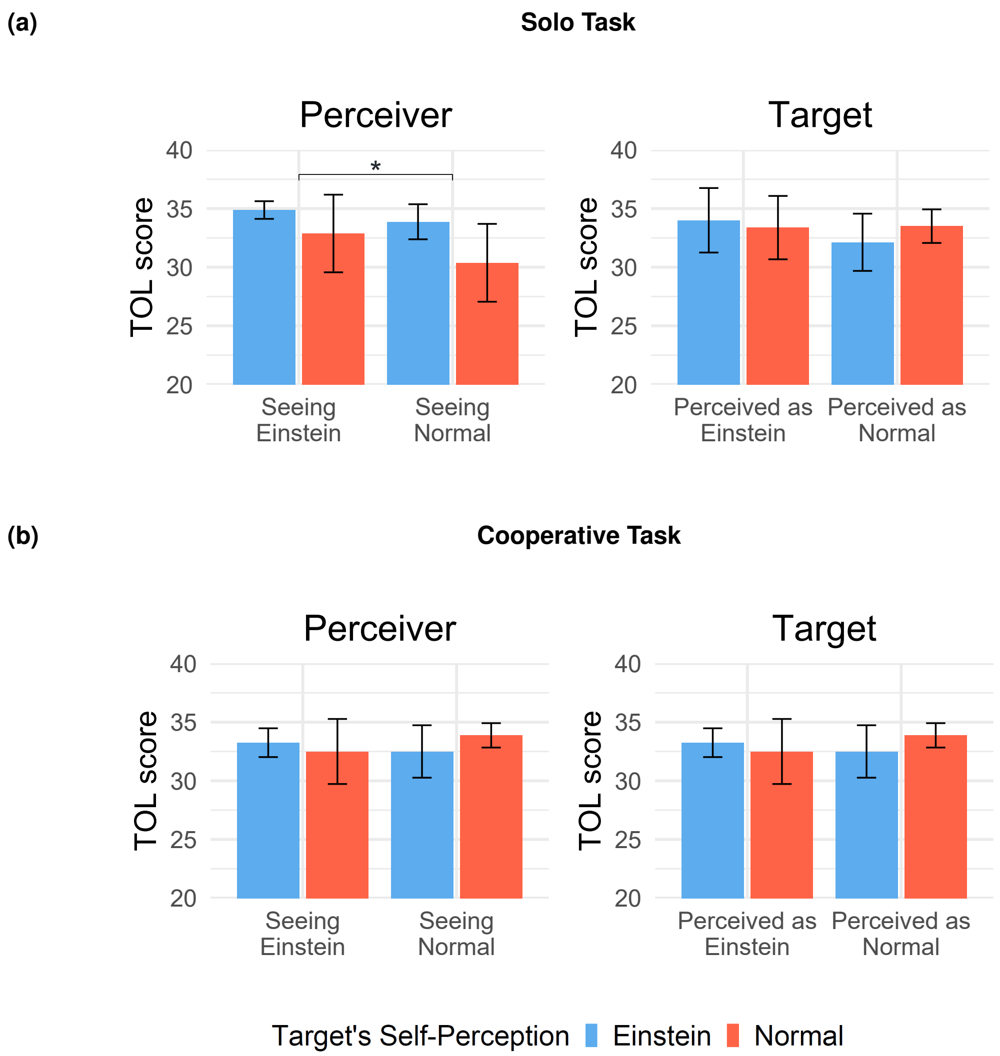

Figure 6.4: Average TOL scores of the target and the perceiver during their solo (a) and cooperative (b) task. The score of the perceiver in the solo task was significantly better when the target was seen as Einstein instead of Normal.

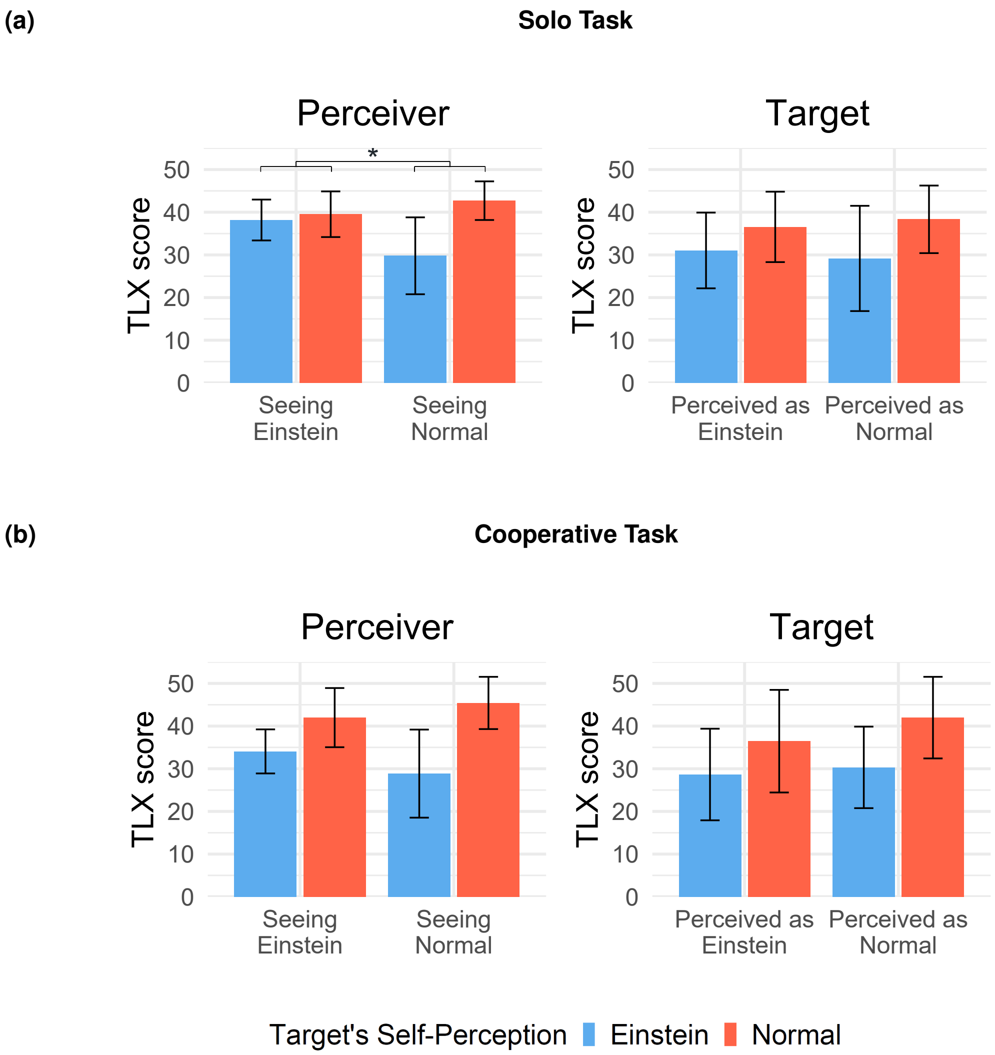

Figure 6.5: Average NASA-TLX scores of the target and the perceiver during their solo (a) and cooperative (b) task. The perceivers' task load in the solo task depended on how the target perceived the own avatar. When the targets perceived themselves as Einstein, the perceivers had a significantly lower task load. In all conditions, the NASA-TLX scores from target or perceiver were lower, when the target's self-perception was Einstein. This indicates that there is a systematic relation between how the participants perceived themselves and a behavioral change causing a lower workload for their companions when they saw themselves as Einstein.

$F(1,14) = 6.586$, $p = .022$, $\eta_p^2 = .319$. There was no interaction effect of EXTERNAL PERCEPTION × SELF-PERCEPTION, $F(1,14) = 2.419$, $p = .142$, $\eta_p^2 = .147$, on the NASA-TLX score. Thus, for the solo task we found that the perceivers' task load depended on how the targets perceived their avatar. When the targets perceived themselves as Einstein, the perceivers had a significantly lower task load (see Figure 6.5a).

6.3.1.4 Cooperative NASA-TLX Scores

We found no significant main effects of EXTERNAL PERCEPTION, $F(1,14) = 1.556$, $p = .233$, $\eta_p^2 = .052$, SELF-PERCEPTION, $F(1,14) = 4.518$, $p = .051$, $\eta_p^2 = .224$, and no interaction effect of EXTERNAL PERCEPTION × SELF-PERCEPTION, $F(1,14) = 2.694$, $p = .123$, $\eta_p^2 = .213$, on the NASA-TLX score. Thus, the perceivers' scores during the cooperative task were not affected by the targets' avatar (see Figure 6.5b).

6.3.1.5 Presence

We did not find a significant main effect of EXTERNAL PERCEPTION, $F(1,14) = 0.669$, $p = .427$, $\eta_p^2 = .045$, and of SELF-PERCEPTION, $F(1,14) = 1.415$, $p = .254$, $\eta_p^2 = .091$, and no interaction effect of EXTERNAL PERCEPTION × SELF-PERCEPTION, $F(1,14) = 0.283$, $p = .603$, $\eta_p^2 = .019$, on the IPQ score indicating that presence did not significantly differ between the conditions.

6.3.1.6 Social Presence

We found a significant main effect of EXTERNAL PERCEPTION, $F(1,14) = 4.759$, $p = .047$, $\eta_p^2 = .253$, however, not of SELF-PERCEPTION, $F(1,14) = 0.917$, $p = .354$, $\eta_p^2 = .061$, and no interaction effect of EXTERNAL PERCEPTION × SELF-PERCEPTION, $F(1,14) = 0.578$, $p = .460$, $\eta_p^2 = .039$, on the social presence scores. We assume that the external appearance of the target's avatar changed the level of social presence of the perceiver. Figure 6.6 depicts the average social presence scores.

6.3.1.7 Body Ownership

Individual multifactorial ART ANOVAs on the items of the BRQ as used by Banakou et al. (2018) show significant main effects of EXTERNAL PERCEPTION, $F(1,14) = 4.722$, $p = .047$, $\eta_p^2 = .252$, and of SELF-PERCEPTION, $F(1,14) = 5.935$, $p = .028$, $\eta_p^2 = .297$, but no interaction effect of SELF-PERCEPTION × EXTERNAL PERCEPTION,

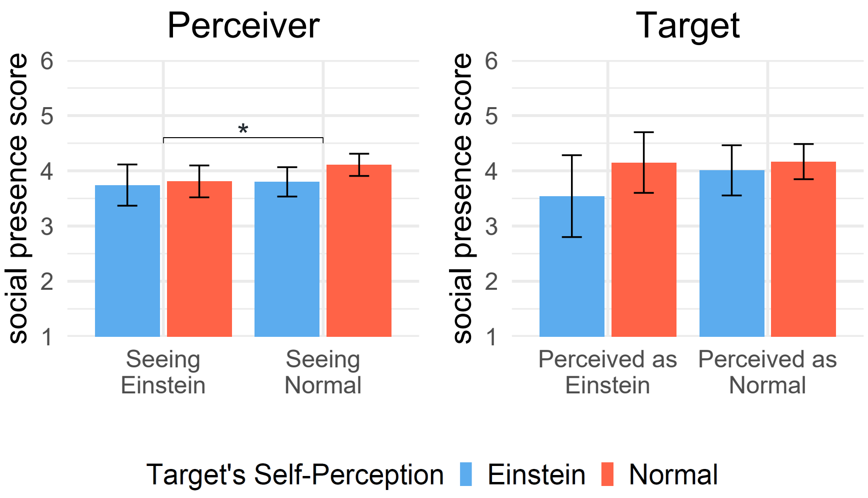

Figure 6.6: Social presence scores of the target and perceiver. The external appearance of a target's avatar changed the level of social presence for the perceiver.

$F(1,30) = 2.250$, $p = .155$, $\eta_p^2 = .138$, on the measure *features*. The measures of *vrbody* (all with $p > .333$), *mirror* (all with $p > .270$), *twobodies* (all with $p > .321$), and *agency* (all with $p > .227$) show no significant main or interaction effects. Thus, perceived features of Einstein that did not resemble one's own body were affected through the external appereance of the targets' avatar and how the targets saw themselves.

6.3.2 Target

There we no significant main effects of External Perception, Self-Perception, and no interaction effects of External Perception × Self-Perception on the target's solo and cooperative TOL scores, solo and cooperative NASA-TLX scores, and presence, social presence, and BRQ scores (all with $p > .05$).

6.4 Discussion

In this study, we investigated the effects of self- and external perception on cognitive task performance in VR. A total of 32 male participants performed a TOL task. We investigated the effects on cognitive performance when one participant (target) was perceived as Einstein even when another participant (perceiver) perceived the target as a normal young adult avatar. We found that the external perception of the target significantly affected the cognitive performance of the perceiver. Thus, cognitive performance increased while seeing another person as Einstein. Furthermore, we found that perceivers who saw targets perceiving themselves as Einstein had a significantly lower task load. While inferential statistics revealed no significant effects on the cooperative task, descriptive results are in line with the solo task.

We assume that the cooperative TOL task, used to determine performance in collaborative problem solving, did not show significant effects as the task was originally designed for individual problem solving and, thus, not sensitive enough for determining effects during collaboration. In addition, the perceivers' social presence and the degree to which the perceived features resemble the own body significantly decreased when the perceiver saw another person as Einstein instead of a normal young adult. We assume that being together in a virtual room with the universally known Einstein who died a long time ago is an unrealistic scenario leading to a significant drop in social presence. Similar was shown in prior investigations which revealed a relationship of the avatars' realistic appearance and the degree of social presence in CVEs (Zibrek & McDonnell, 2019; Zibrek et al., 2018; Bailenson et al., 2005).

Previous work on the Proteus effect suggests that embodying Einstein should cause a higher cognitive performance. This is supported by Banakou et al. (2018) who found that after embodying Einstein, participants had a significantly higher cognitive performance (Banakou et al., 2018). Thus, our results do not support the findings by Banakou et al. (2018), which can be attributed to a number of differences between the study by Banakou et al. (2018) and our study. We measured cognitive performance in VR *while* embodying Einstein in a CVE whereas Banakou et al. (2018) measured cognitive performance *after leaving VR* (Banakou et al., 2018). We, however, would expect that cognitive performance should be highest while embodying Einstein. Additionally, exposure time also differed. Banakou et al. (2018) embodied participants for 12 minutes in Einstein, our participants embodied Einstein for around 30 minutes per condition resulting in being Einstein for 60 minutes (Banakou et al., 2018). The Proteus effect suggests that cognitive performance should increase the longer Einstein is embodied. Consequently, we should have observed a stronger effect on cognitive performance, which was not the case. That is why we assume that being and interacting with another person might have interpersonal and disruptive effects confounding an increasing cognitive performance while being Einstein.

The behavioral confirmation paradigm would suggest that being perceived as Einstein should result in a behavior that resembles Einstein. Thus, participants embodied as Einstein should change their behavior according to how they expect that Einstein would behave. As Einstein is a stereotype for superior intelligence, one should behave according to the expectation of having high intelligence when embodying Einstein. We, however, found neither effects on cognitive performance nor perceived task load of the person embodied as Einstein. As we limited the interaction between participants to observe each other's movement, we assume that the level of social interaction was not sufficient to trigger direct behavioral confirmation effects. Nevertheless, perceived task load depends on how the other person perceives their own body. There are a number of potential explanations: One might assume that if the target performs the task faster, this could encourage the perceiver. We, however, found no effects on TCT indicating that the targets' speed did not change. We assume that there must be more underlying factors of social interaction and the targets' behavior that systematically or subconsciously communicates that someone embodied as Einstein is confident or assertive in doing the task.

We found significant effects of the targets' own perception on task load of the perceiver. In all conditions, the TLX scores were lower, when the target's self-perception was Einstein. This indicates that there is a systematic relation between how the participants perceive themselves and a behavioral change causing a lower workload for their companions. However, neither the Proteus effect nor the theory of behavioral confirmation can explain that increased cognitive performance. The increased TOL score might be explained by an increase in perceived competition and engagement due to competitive behavior. Research in psychology suggests that competition can increase performance but that the effect is mediated by effects on the individual goals (Elliot & Church, 1997; Murayama & Elliot, 2012). Performance-approach goals, trying to do well relative to others, increase performance and performance-avoidance goals, trying to avoid doing poorly compared to others, decrease performance. We assume that seeing Einstein might have motivated participants to try doing well relative to the other participant. Similarly, targets seeing themselves as Einstein might have displayed behavior that motivated perceivers, who had a lower task load. While effects mediated by competition are plausible, we cannot rule out other explanations.

The impact of learning caused by order effects has to be considered in repetitive tasks as well. Learning effects could increase the amount of unsystematic variance making it more difficult to find a significant difference between conditions. Although participants performed better in the TOL game in later stages of the experiment, we could find a significant effect of external perception on the TOL score. Since we counterbalanced the conditions, we can rule out that it was the process of learning that enhanced participants' cognitive performance when the target was perceived as Einstein compared to a young adult.

6.5 Conclusion

This chapter described a study to investigate the effects of self- and external perception. We found that seeing another person as Einstein as well as seeing persons who perceive themselves as Einstein can significantly affect the user. While previous work showed that embodying avatars can have effects, we show that being with someone embodying different avatars can affect the user as well. While this effect cannot be explained by the Proteus effect or behavioral confirmation, we assume that other psychological mechanisms, such as effects of competition might explain the impact of avatars on users. From an HCI perspective, however, the conclusion is rather simple. When designing avatars for CVEs it is important to not only consider effects on the user embodying the avatar but also effects on other users.

Future work should further explore the effects of self- and external perception. We found effects on cognitive performance and perceived task load. We, however, assume that other effects could be even stronger. If embodying avatars can reduce racial biases (Peck et al., 2013; Maister et al., 2013), it is likely that seeing certain avatars can further reinforce the effect. To avoid gender mismatches between participant and avatar (Schwind et al., 2017b), we only investigated avatars' effects on male users. Therefore, the embodiment of "Marie Curie" and the impact on female users could provide further insights into the underlying mechanisms. Future work should also find more ways to quantify the Proteus effect. If effects are indeed mediated by the Proteus effect, we need ways to quantify it to predict the effect of different avatars on users.

7

Conclusion

This thesis investigates the Proteus effect and how this phenomenon can be utilized in the field of HCI to improve user performance in VR. We first conducted the seminal RHI to learn about the concept of body ownership and the consequences for the real body. We also explored BOIs in VR using realistic and abstract virtual hands with altered body structures to learn more about the fundamentals of embodying avatars with features that strongly differ from the own physical self. We then investigated the Proteus effect using full-body avatars with muscular, athletic, and “intelligent-looking” appearances in VR. This chapter summarizes the contributions of this thesis and discusses future directions regarding the Proteus effect and the opportunities for using this phenomenon in HCI. We provide an overview of the implications for HCI and present design guidelines to support designers and researchers for the creation of avatars that can enhance performance within virtual worlds.

Parts of this chapter are based on the following publications:

Kocur, M., Henze, N., & Schwind, V. (2021c). “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*, pp. 1–3. DOI: 10.5283/epub.45543.

Kocur, M., Henze, N., & Schwind, V. (2021d). “Towards an Investigation of Avatars’ Sweat Effects during Physical Exertion in Virtual Reality.” In: *Mensch und Computer 2021 - Workshopband*. Ed. by C. Wienrich, P. Wintersberger, & B. Weyers. Bonn: Gesellschaft für Informatik e.V.. DOI: 10.18420/muc2021-mci-ws16-261.

Kocur, M., Roth, D., & Schwind, V. (2020d). "Towards an Investigation of Embodiment Time in Virtual Reality." In: *Mensch und Computer 2020 - Workshopband.* Ed. by C. Hansen, A. Nürnberger, & B. Preim. Bonn: Gesellschaft für Informatik e.V.. DOI: 10.18420/muc2020-ws134-339.

7.1 Summary of Contributions

In Chapter 3, we explored the RHI to determine whether the same principles for inducing BOIs that apply in the real world also apply in virtual worlds. We found that the virtual rubber hand resulted in similar and comparable effects on the experienced body ownership as a physical rubber hand in the real world. These findings provide empirical evidence that the methods applied in the real world to induce BOIs (i.e., using visuo-tactile synchrony) can be used and adopted to elicit BOIs in VR with similar effects on users (RQ1). We also found a decreased skin temperature of the real hand while embodying the rubber hand, which demonstrates that BOIs can even affect physiological responses controlled by the autonomic nervous system.

In Chapter 4, we explored the effects of avatars with altered body structures to find out whether and how violations of human anatomy influence the behavior and user experience in VR. If avatars with altered body structures were accepted and did not negatively affect the interaction in VR, such changes could be promising to induce behavioral changes and allow users to experience how it feels to embody virtual bodies with characteristics that deviate from human anatomy. Inspired by stylized cartoon characters with less than five fingers from video games and animated movies, e.g., *Mickey Mouse*, we explored how missing fingers of a virtual hand affect the experience, behavior, and performance in VR. We found that removing fingers of a virtual hand can cause negative emotional responses such as phantom pain, decrease the sense of presence and change the behavior resulting in a decreased task performance in VR (RQ2). Hence, negative effects have to be considered when using avatars with bodily structure violations and strong deviance from the users' physical self.

Based on these findings, we embodied users in human-like full-body avatars and changed the visual characteristics to induce the Proteus effect with the aim to enhance the performance in VR. In Chapter 5, we investigated the effects of an avatar's characteristics that are associated with high physical abilities on the users' VR experience and physical performance. We found that muscular avatars can increase performance and decrease the perception of effort during physical tasks (RQ3). Additionally, the users' HR responses were reduced while embodying avatars with an athletic appearance (RQ4). We also found that the sense of presence and the experienced body ownership were affected by the avatars' appearance. The results illustrate that embodying "high-performing" avatars can positively affect users during physical effort. The findings also demonstrate the psychophysiological impact of avatars on users embodying them and support the hypothesis that avatars can even affect physiological responses.

In Chapter 6, we aimed to induce the Proteus effect by embodying users in an Einstein avatar as a stereotype for a superior intelligence to investigate whether we can also enhance the cognitive performance and VR experience in a CVE. We did not show the Proteus effect, which supports the assumption that other psychological mechanisms such as competition can mediate the effects that originated from the Einstein avatar in CVEs (RQ5). However, we found that seeing another user as Einstein resulted in increased cognitive performance but decreased sense of social presence. In social settings, it is therefore important to not only consider effects on the users embodying the avatar but also the effects on other users sharing the same virtual space.

7.2 Utilizing the Proteus Effect

In this section, we discuss the utilization of the Proteus effect in the context of HCI and potential areas of application. We found that the embodiment of avatars with features connected to high physical abilities can make users perceive a physical exercise as less intense compared to avatars that are rather regarded as non-athletic. Due to evolutionary mechanisms, humans do not like to exert themselves to save valuable energy resources and are therefore considered "inherently lazy" (Marcora, 2016). As such, sports scientists argue that the perception of effort is a barrier to regular physical activity (Bauman et al., 2012; Marcora, 2016). For this reason, a reduction of the perceived exertion can foster exercise adherence and increase physical activity (Pageaux, 2014). For designers and researchers of immersive exergames and VR fitness applications, the usage of "high-performing" avatars can, therefore, be promising to positively affect users and create more effective applications. Our athletic and muscular avatars were able to reduce the perception of effort by approximately 1 point on average on the 6-20 ratings of the RPE scale compared to the non-athletic and non-muscular avatars. Interestingly, previous work found that caffeine can also reduce the perception of effort by 1 point on the same scale (Doherty & Smith, 2005). This is one reason why athletes consume caffeine before workouts and competitions (Del Coso et al., 2011). Apparently, this does not prove that the effects that originated from the embodiment of an avatar are the same as the effects caused by caffeine. However, such findings indicate the potential and power of avatars as tools to induce positive effects on users during exercise.

This becomes even more evident regarding the psychophysiological impact of avatars on users. We found that athletic avatars reduced the HR while cycling on an ergometer in VR. These findings show that the effects caused by the embodiment of certain avatars are not only limited to the users' subjective experience of exertion but can also affect physiological responses to physical exercise. The correlation between the perception of effort and the HR is in line with embodied cognition theories that assume a strong bond between the human mind and the body (see Section 2.2.6 Embodied Cognition). As we also found effects on autonomic temperature regulation processes caused by the embodiment of a rubber hand, the impact on HR responses is further evidence that the embodiment of avatars with certain characteristics can affect physiological responses controlled by the autonomic nervous system. On the other hand, such psychophysiological effects can also entail risks that have to be considered when designing avatars for VR exercise systems. In Section 5.4.9, we addressed potential adverse effects.

The question remains whether a reduction of the HR is actually a positive or negative outcome. If a reduced HR is an indicator for a reduced perception of effort, we consider this as positive. However, one might also argue that a decreased HR response is the outcome of a reduced physical activity, which can be considered negative. Arguably, users of VR exercise systems could avail of a higher physical activity to get enhanced exercise benefits. Hence, we argue that a deeper understanding of the impact of avatars to harness the Proteus effect in an optimized way is still required not to negatively affect the users of such applications. Consequently, future work should further explore the promising findings of our work to maximize the utilization of this phenomenon.

In contrast to physical settings, we could not replicate findings from previous work showing enhanced performances during cognitively demanding tasks due to the embodiment of avatars with features associated with high cognitive abilities. In our study, users embodied in Einstein did not perform better than when embodied in a casual avatar. We discussed reasons for the lack of enhanced cognitive performance in Section 6.4. In line with theories from social psychology (Snyder et al., 1977), we argue that the mutual impact of avatars in CVEs can moderate or even extinguish the Proteus effect. However, we found that the other users were positively affected by the Einstein avatar resulting in increased cognitive performance. As a certain degree of cognitive effort and performance is needed in all kinds of human activities, designers and researchers should be aware that in CVE the embodiment of stereotypical avatars to prime attributes such as a high intelligence can be motivating and engaging for other users. In the light of the current debate about the "metaverse" (Ball, 2020; Sparkes, 2021), one of the main visions of VR technology in the future is a *social* immersive virtual world with a functioning economy where millions of users can interact with each other and experience all kinds of events similar to the real world, e.g., concerts, business meetings, or playing games. This *social* aspect of VR indicates that it is important to gain a deeper understanding of the interpersonal perception of multiple users sharing the same virtual space. Consequently, more research is required to learn about the interaction of the self- and external perception to create more effective avatars for social virtual worlds.

Overall, our work showed the potential of avatars and the Proteus effect to positively affect users during interaction in VR. We found that certain avatars can make users perform better in VR than other ones. Hence, we showed that it is possible to utilize the Proteus effect to improve the performance in VEs. However, we also found effects on important quality attributes of VR applications such as a reduced sense of presence or experienced body ownership. Therefore, it is important to consider that our work does not allow us to definitely conclude that the used avatars enhanced the overall VR experience. This means that a more effective and efficient interaction does not automatically result in an improved VR experience. In other words, users could exert more force or have a decreased HR while embodying a muscular or athletic avatar. However, the experience of embodying a non-muscular or non-athletic avatar could be simply more exciting and interesting regardless of the actual performance. As there is no invariably direct relationship between performance and experience, more research building upon our work is necessary to learn more about harnessing the Proteus effect in the context of HCI and VR.

7.3 Implications

In this section, we present a set of design guidelines for researchers and designers of virtual avatars who aim at utilizing the Proteus effect to enhance users' performance in VR. These derived guidelines are based on experimental studies conducted in this thesis alongside empirical observations from previous work on avatar creation for immersive VEs in general (e.g., Dewez et al., 2021; Schwind, 2018), and the Proteus effect in particular.

Use salient characteristics

Avatars with explicit identity cues more likely elicit the intended concepts and, therefore, trigger the desired behavioral changes. Hence, designers can avoid ambiguity as the salient attributes of an avatar reduce the risk that users overlook them or emphasize different aspects of the avatar resulting in misinterpretation. Hence, gentle exaggerations of the avatar's appearance to highlight the desired attributes while still maintaining a certain degree of realism and anatomical plausibility can be beneficial for inducing the Proteus effect, e.g., a high muscle mass or low body fat proportions. However, as previous work found that avatars with idealized characteristics that are non-achievable for users can be demotivating and cause dissatisfaction (Koulouris et al., 2020), it is important to balance the representation of the visual attributes to provide perceptible affordances without dissociating the users from the avatar.

Every user is unique

This principle is widely known in the field of HCI and user experience design and means that there is no average user. Users have their own predispositions and skills that need to be considered during the design process of interactive systems. Apparently, this principle also applies to immersive virtual worlds. When using the Proteus effect, the users' stereotypical assessments have to be anticipated to predict the expected behavior in VR. However, stereotyping can be a highly individual process depending on a variety of contributing factors. We, for example, could not decrease the physical performance when embodying participants in non-muscular compared to muscular avatars during physical exercise. It seemed that the non-muscular avatars were associated with high athleticism due to the low body fat rather than with limited physical power. This example illustrates the complexity of designing appropriate avatars which represent such characteristics that elicit the desired users' associations to trigger the expected effects. If users are unfamiliar with the used stereotypes, perceive them differently than predicted, or even avoid their activation, the expected behavioral changes can fail to occur or even be misleading. To reduce the variance in the behavioral responses and, therefore, minimize the risk of unintended effects, the characteristics of the target population, as well as the applied stereotypes, have to be well-known.

The field of Games User Research offers a collection of methods used in the game development process to gain a thorough understanding of players (Madlock, 2018). Early in the development process, it is inevitable to determine and understand potential players of a game. In line with this notion, we, for example, conducted an online survey to find out how to design athletic avatars and determine characteristics that are associated with athleticism and high cycling performance (see Section 5.4.2). We decided to use renderings of avatars with different proportions of body fat and muscularity and evaluated them to understand the users and how they assessed the avatars in terms of athleticism. This process allowed us to choose avatars that were able to reduce the perception of effort and HR responses during cycling in VR. Consequently, the involvement of users in the early stages of the character design process is inevitable to be able to create avatars that induce the Proteus effect and improve performance in a targeted manner.

The Proteus effect is context-sensitive

Researchers agree that the Proteus effect is a diverse phenomenon that highly depends on the context of the virtual scenario. Banakou et al. (2018) found that users who embodied an Einstein avatar in a single-user VE had a higher cognitive performance compared to a casual embodiment. We, however, could not replicate these findings in a CVE where two users played a cognitively demanding game while sharing the same virtual space. We argue that competition or other psychological mechanisms underlying social interaction, e.g., behavioral confirmation (Snyder et al., 1977), are seminal moderators, and, therefore, mediate or even extinguish the Proteus effect. Consequently, the context of a virtual scenario can affect the degree of behavioral changes caused by the Proteus effect, e.g., being alone as opposed to being together with others in a VE. Besides the reciprocal impact of multiple characters, other contextual factors such as the narrative created through the scenario and the atmosphere and mood created through the design of the environment have to be considered when applying this phenomenon.

Use a task fitting the activated stereotype

It is important to allow the user to perform the behavior that is associated with the stereotypical appearance of the avatar and act in a stereotype-congruent way. For example, when a stereotype for high physical abilities using an athletic avatar is activated during the virtual embodiment, the user should be able to perform a physical task in or outside of VR. If there is a mismatch between the elicited stereotype connected with the avatar's appearance and the task at hand, the users may change the behavior in an undesired way, which in turn can result in negative effects on the performance and VR experience., e.g., embodying Einstein during a physically demanding task. Instead of boosting the physical performance, the Einstein avatar could activate age-related concepts that could possibly decrease performance during physical exertion.

Consider the impact of the body ownership illusion

Previous work found that the BOI modulates the behavioral and perceptual changes caused by the avatar. Our findings tend to confirm this assumption and show a relationship between the BOI and the Proteus effect. Therefore, it is important to establish a feeling of embodying the avatar to engage users and make them more connected to the avatar and the entire virtual experience. While it is not a mandatory condition to induce a certain level of BOI for the Proteus effect to occur, researchers and designers should be aware that the more users experience the avatar as their own body, the more likely they adopt the avatar's characteristics and adapt their behavior to conform to the common expectations associated with the avatar's identity.

Consider potential negative effects of altered body structures

As VR allows to depict the avatar in any desired and imaginable style, it is possible to create avatars with body structures that deviate from the human norm. We found that virtual hands with a reduced number of fingers can decrease the sense of presence and cause negative emotional responses such as phantom pain. Such negative sensations even increase when using hands with a realistic appearance. Our results also indicate that users' adapted their behavior and the way of interacting with the VE based on the visual appearance of the virtual hands. Even if altered body structures seem promising to create a novel experience and allow users to experience how it would feel to have a body with anatomical characteristics that differ from the own ones (e.g., missing fingers, prolonged limbs), it is important to consider that negative effects can occur (particularly at high levels of realism). As users are very used to their own body's characteristics, strong deviations can therefore create unpleasant effects. Such negative effects caused by atypicalities of an avatar's physical structures are in line with findings from investigations on the uncanny valley. Schwind et al. (2018b) recommends avoiding altered body structures for realistic characters as atypical features at high levels of realism can elicit the uncanny valley. In line with our findings, however, the authors argued that abstract characters with a reduced realism are less susceptible to the uncanny valley despite atypicalities (e.g., *Mickey Mouse* has four fingers or *Octodad* possesses tentacles; Young Horses, 2014). Hence, these results suggest that users better accept deviations from the human norm when embodying avatars with consistently unrealistic characteristics (Schwind et al., 2018b).

7.4 Limitations and Future Work

Although the Proteus effect is a valid phenomenon with consistent effect sizes between small and medium (Ratan et al., 2019), we learned that it is also diverse in nature and depends on a variety of contributing factors. As we aimed at minimizing interference from confounding factors to optimize the Proteus effect and precisely measure performance in VR, we focused on a homogeneous population used in our studies. Thus, we minimized the discrepancy between the users' attributes and the avatars' basic characteristics (e.g., skin color, gender, body composition). Due to the users' diversity, however, it is therefore difficult to generalize the effects caused by the avatar's appearance and predict whether they translate to other settings with different users. Hence, it is important to further explore this phenomenon with more diverse samples (e.g., athletes vs non-athletes) in natural settings to gain a deeper knowledge about its dynamics. As gender diversity should be considered during the design of avatars to achieve high user identification and body ownership, it is important to learn about gender differences in the body image in the context of the Proteus effect. For example, future studies could investigate gender swaps (e.g., male users embodying female avatars) during physical or cognitive exertion to obtain valuable insights into the design of the avatar's characteristics and to learn how to generalize the effects across different groups of users.

To further reduce the deviations of the avatars' characteristics from the users' own physical attributes, we propose to investigate more subtle changes not to negatively affect the quality of the VR experience (e.g., the sense of presence) and still maintain a certain degree of body ownership and identification. Sweating, for example, is a natural response to physical exertion. Hence, future studies could explore how visualizing sweat effects on the avatar's skin affects the users' physical performance and perceived effort. Designers could therefore prime the intended concepts (e.g., not sweating during exertion as a sign of increased physical abilities) without deteriorating the discrepancy between the own physical body and the avatars' characteristics. While a sweating avatar during exertion could result in a more vivid and realistic VR experience, visualizing sweat could also cause adverse effects on users' physical performance (e.g., increased sweating during exertion as a sign of decreased fitness).

In our studies, the participants were provided with predefined avatars. Avatar customization could be a further possibility to foster embodiment and user identification, as users can individually design their own avatar and express themselves. Based on simple instructions and possible personas (e.g., an avatar with a high educational degree and IQ), users could equip the avatars with characteristics (e.g., glasses, attire) that are personally associated with certain concepts (e.g, a high level of intelligence). Hence, future studies could explore whether customizing an avatar can elevate the Proteus effect due to a higher sense of body ownership of the avatar and increased identification.

Besides the visual appearance of avatars in terms of clothes or body composition, other features such as the voice, facial expressions, or other non-verbal cues could also be used to induce behavioral changes. As described in Section 2.2.6, research should further investigate users' behavior and perception based on embodied cognition approaches. For example, previous work found that objects within reach appeared to be farther away when participants had to move their arms against a strong counterforce compared to a weak counterforce. As human perception and behavior are connected, such perceptual changes automatically affect the own behavior (Chartrand & Bargh, 1999). Hence, instead of manipulating the visual characteristics of an avatar, it seems promising to positively affect users by changing the animations and movements of an avatar. For instance, inducing artificial latency of an avatar's movements could simulate counterforces and create the feeling of sluggish motion. On the other hand, machine-learning-based algorithms to predict future movements (Schwind et al., 2020) could create a feeling of airiness and lacking counterforces, which could, in turn, result in a feeling of increased flexibility. Hence, slightly manipulating the synchrony of users' motion and the avatar's reaction without deteriorating the sense of agency and ownership could also evoke behavioral changes positively affecting the VR experience.

A further aspect that is important for the utilization of the Proteus effect is the duration of this phenomenon. So far, this body of work explored the Proteus effect on the short term in single sessions. Hence, it remains unclear whether users can benefit from this phenomenon from a long-term perspective, and how it evolves over time. Besides, future work should also address whether the embodiment time, as well as multiple exposures to the avatars, affect the resulting changes caused by the avatar's appearance. As users may quickly get used to their avatars and, therefore, ignore the deviations between their own body and the virtual appearance, habituation effects may occur attenuating the Proteus effect over time. Surprisingly, it is still little known about the effects of being immersed in VR for a longer period of time. Steinicke and Bruder (2014) reported that a participant who spent 24 hours in VR using an HMD experienced simulator sickness and a dry eye syndrome due to the ergonomics of the HMD. Even though it is obvious that VR technology will steadily become more and more sophisticated, such findings still suggest that negative effects caused by the (prolonged) consumption of VR have to be considered when designing immersive applications and intending to leverage the Proteus effect. Consequently, research would benefit from systematic investigations on the time facets of VR usage in general.

To induce the Proteus effect, we typically used the "mirror paradigm" by placing a virtual mirror in front of the users to enable them to constantly perceive their body during interaction in VR to facilitate the sense of embodiment. While the "mirror paradigm" is applicable for indoor scenarios and virtual replicas of gyms, mirror-like reflections in natural settings are very scarce and, therefore, mirrors are rather inappropriate for natural outdoor VR experiences. Hence, future work should explore different design possibilities to promote the embodiment of the avatar and replace artificially placed mirrors in a virtual scene. For example, designers could take advantage of natural reflections of surrounding objects or could emphasize tasks where crucial body parts for the Proteus effect are visible while performing them.

Researchers need to know how to measure behavioral changes caused by the embodiment of avatars. Performance measures, e.g exerted force, perceived exertion, walking speed (Reinhard et al., 2020), or cognitive performance, may pose one opportunity to indirectly quantify the Proteus effect. More complex behavioral changes, which provide profound insights about the users' experience but can hardly be evaluated through quantitative methods, could be assessed qualitatively by independent observers. For example, embodying nonhumanoids such as animals may lead to behavioral responses such as flapping the arms while embodying a bat (Andreasen et al., 2019) or crawling on all fours while being embodied in a tiger (Krekhov et al., 2019a). Independent observers could analyze these complex behavioral responses by observing the users during virtual embodiment to identify behavioral patterns. As already shown in previous work investigating the recognition of musical genres based on dancing behavior (Carlson et al., 2020), automatic classification algorithms could further be used to analyze recorded motion data and identifying certain behavior. Even if these approaches may be promising to better understand the users' experiential responses while being immersed in VEs, more research about the Proteus effect is needed to gain a deeper knowledge about this phenomenon to learn how to optimize its utilization.

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List of Acronyms

2AFC	two-alternative forced-choice
ANOVA	analysis of variance
AR	augmented reality
ART	Aligned Rank Transform
BMI	Body Mass Index
BOI	body ownership illusion
BRQ	Body Representation Questionnaire
CVE	collaborative virtual environment
FPS	frames per second
HCI	human-computer interaction
HIT	Human Intelligence Task
HMD	head-mounted display
HR	heart rate
IAT	Implicit Association Test
IPQ	Igroup Presence Questionnaire
JND	just-noticeable difference
NASA-TLX	NASA Task Load Index
NPC	non-player character
PIS	Player Identification Scale
RHI	rubber hand illusion
RPE	Rating of Perceived Exertion
SPF	self-perceived fitness

TCT task completion time
TOL Tower of London
VAS Visual Analog Scale
VE virtual environment
VR virtual reality