REPLACING THE BODY IN EMBODIMENT

The Relationship Between Avatars and Interoception in Virtual Reality

Julius-Maximilians-Universität Würzburg

Inaugural Dissertation zur Erlangung der Doktorwürde der Fakultät für Humanwissenschaften

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aus Würzburg, Juni 2024

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Replacing the Body in Embodiment:
Human-Computer Interaction, Juni 2024
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Abstract

This thesis examines the relationship between an individual's sense of embodiment towards an avatar and the processing and awareness of internal body signals (body awareness) in virtual reality (VR) in the context of mind-body interventions.

To do so, I[1] present a systematic literature review, a user experience evaluation of an avatar embodiment system, and a series of five experiments that systematically assess the effects of discrepancy between the user's corporeal body and their avatar. The systematic literature review gives insights into the current landscape of VR mind-body interventions and combines them with a framework for designing and evaluating VR-based intervention modules. This framework forms the basis for the design of my empirical work. The user experience evaluation study presents the technical basis of my research. It maps the general processes for creating photorealistic personalized avatars. Further, it presents an embodiment system to control and animate these avatars in VR and a general experimental procedure before and within VR, ensuring a positive experience. The first two experiments on the sense of embodiment towards an avatar and body awareness examine the relationship between the two variables and the effect of VR in a close-to-reality scenario on both of them. The other three experiments examine the effects of discrepancy between the user's corporeal body and their avatar. They target non-similar avatar appearance, mid-experience perspective changes, avatar visibility, and virtual out-of-body experiences.

The empirical studies of my thesis revealed some key findings:

1. Users experienced a reduced sense of embodiment towards their avatar compared to their corporeal body.
2. Embodying an avatar was accompanied by a reduced body awareness.
3. The sense of embodiment was positively related to body awareness on several dimensions. Some of these served as mediators between the effects of VR and avatar discrepancy on body awareness.
4. However, increasing the discrepancy between the avatar and the user's corporeal body did not necessarily have a negative effect on body awareness. Rather, embodying non-personalized avatars and/or changing into an outside perspective increased body awareness compared to embodying a personalized avatar from a first-person perspective.

The presented research provides insight into the interplay of avatar presentation, sense of embodiment, and body awareness in the context of VR mind-body interventions. From the results, I draw conclusions about the application in therapeutic and non-therapeutic settings. I discuss these results in the context of psychological embodiment research and the role of the body in mental health. Finally, I present a set of outlines for future work towards integrating body awareness in virtual mind-body interventions.

[1] I want to highlight that while, except for the chapter overview, I am writing this thesis in the first person singular, I value the work of my colleagues and co-authors. A great part of the findings in this thesis result from constant communication, interdisciplinary cooperation, and mutual support.

Abstract (German)

Diese Arbeit untersucht die Beziehung zwischen dem Gefühl, einen Avatar zu verkörpern (Gefühl der Verkörperung) und der Verarbeitung und Wahrnehmung von internen Körpersignalen (Körperaufmerksamkeit) in einer virtuellen Realität (VR) im Kontext körperpsychotherapeutischer Interventionen.

Hierfür wurde eine systematische Literaturübersicht, eine Studie zur Evaluation der Nutzungserfahrung eines Avatar-Verkörperungssystems, sowie eine Reihe von fünf Experimenten durchgeführt, die systematisch die Effekte von Diskrepanz zwischen dem leiblichen Körper der Benutzer:innen und ihrem jeweiligen Avatar untersuchen. Die systematische Literaturübersicht gibt Einblicke in die aktuelle Landschaft der VR-basierten körperpsychotherapeutischen Interventionen und kombiniert sie mit einem Framework für deren Gestaltung und Bewertung. Dieser Rahmen bildet die Grundlage für das Vorgehen in den empirischen Studien.

Die Studie zur Evaluation der Nutzungserfahrung stellt die technische Grundlage meiner Forschung vor. Sie bildet einen Prozess zur Erstellung fotorealistischer, personalisierter Avatare ab, welcher in den späteren Studien wieder aufgegriffen wird. Darüber hinaus wird ein Verkörperungs-System zur Steuerung und Animation dieser Avatare in VR sowie ein allgemeiner Versuchsablauf vor und in VR vorgestellt, der ein positives Nutzungserlebnis gewährleistet. Die ersten beiden Experimente zum Gefühl der Verkörperung und zur Körperaufmerksamkeit untersuchen die Beziehung zwischen diesen und die Auswirkungen von VR in einem realitätsnahen Szenario. Die anderen drei Experimente vergrößern die Diskrepanz zwischen dem Körper der Nutzer:innen und ihren Avataren. Sie befassen sich mit Abweichungen im Aussehen der Avatare, mit Perspektivenwechseln während eines VR-Erlebnisses, der Sichtbarkeit der Avatare und mit virtuellen außerkörperlichen Erfahrungen.

Die empirischen Untersuchungen im Rahmen dieser Dissertation lieferten einige Erkenntnisse:

1. Nutzer:innen empfanden ein geringeres Gefühl der Verkörperung gegenüber ihrem Avatar als gegenüber ihrem leiblichen Körper.
2. Die Verkörperung eines Avatars reduzierte die Körperaufmerksamkeit der Nutzer:innen.
3. Das Gefühl der Verkörperung war in mehreren Dimensionen positiv mit der Körperaufmerksamkeit verbunden. Einige davon dienten als Mediatoren für die Auswirkungen von VR und Avatar-Diskrepanz auf die Körperaufmerksamkeit.
4. Eine größere Diskrepanz zwischen dem Avatar und dem leiblichen Körper wirkte sich jedoch nicht unbedingt negativ auf die Körperaufmerksamkeit aus. Die Verkörperung eines nicht-personalisierten Avatars und/oder der Wechsel in eine Außenperspektive steigerte die Körperaufmerksamkeit im Vergleich zur Verkörperung eines personalisierten Avatars aus der Ich-Perspektive.

Die vorgestellte Forschung gibt Einblicke in das Zusammenspiel von Avatar-Präsentation, Gefühl der Verkörperung und Körperaufmerksamkeit im Kontext von VR-basierten körperpsychotherapeutischen Interventionen. Aus den Ergebnissen lassen sich Schlussfolgerungen für die Anwendung in therapeutischen und nicht-therapeutischen Szenarien ableiten. Diese Ergebnisse werden im Kontext der psychologischen Verkörperungs-Forschung und der Rolle des Körpers in der psychischen Gesundheit diskutiert. Abschließend werden eine Reihe von Skizzen für zukünftige Arbeiten zur Integration von Körperaufmerksamkeit in virtuelle körperspychotherapeutische Interventionen präsentiert.

Acknowledgements

I would like to express my sincere gratitude to my two supervisors, Carolin Wienrich and Marc Erich Latoschik. Thank you for your expertise and your invaluable feedback and guidance. Your willingness to answer my questions and listen to my concerns have been pivotal. This thesis would have taken a vastly different direction without your unwavering support and supervision. Carolin, thank you for the honor of being your first research assistant. Your approachability in our collaboration has been immensely rewarding for me. Marc, thank you for emphasizing the importance of charting my own course to achieve success and fulfillment in my work.

Thank you to my closest colleagues, Erik Wolf and David Mal. To Erik, special thanks for reminding me regularly that even the smallest details can be valuable and that every problem can be solved if tackled head-on. To David, thank you for reminding me regularly that there is life beyond theoretical concepts and for our countless brainstorming sessions.

I also express my gratitude to my other colleagues. To the PIIS group: Thank you for the joy of being team partners and growing together over time. To the PsyErgo group: Thank you for welcoming me as a guest when I first arrived. To the HCI group: Thank you for your extensive knowledge sharing. To the ViTraS project team: Thank you for the joyful and productive collaboration. Many thanks to the student assistants Viktor Frohnapfel, Nico Erdmannsdörfer, Marie Fiedler, Lena Holderrieth, Theresa Schell, Lucie Pitters, and Matthias Beck, whose diligent work and active participation have been indispensable.

I want to thank two individuals who inadvertently brought about a turning point in my work: Tobias Grundgeiger, for the phrase "Einfach mal anfangen, einfach mal machen" which marked a turning point for me and without which I might still be stuck in my first study. And Bernd Köhnlein, for handing me the affirmation "So, wie ich es mache, ist es auch gut" which served as a reminder that I can forge my own path rather than following in the big footsteps of others.

My deepest thanks go to my partner Roland Zechner. Thank you for being there for me at every opportunity and for being willing to listen to all my worries, no matter how big or small, justified or unjustified they may seem. Thank you for the long hours of discussion and for never getting tired of supporting me, whether it’s in working overtime in the evening or on weekends or in the battle against myself. Thank you for your unwavering support, for always lending both ears to my concerns, and for your endless encouragement.

Finally, I want to thank my family and friends. Thank you for reminding me that there is a life outside of my work and that my worth as a person is not determined by my work but just by being there. Thank you for the frequent visits and calls, for the distractions, for the leisure time, and for broadening my horizons time and again.

Contents

Extended Summary

Motivation: Virtual Bodies in Therapy and The Body In Mental Health

> We humans have lost the wisdom of genuinely resting and relaxing. We worry too much. We don't allow our bodies to heal, and we don't allow our minds and hearts to heal.
>
> — *Thích Nhất Hạnh*

One could assume that humans are experts at experiencing their bodies. From birth to death, every little moment is experienced through the body, every thought is based on body sensations, and the body is always there to interact with one's surroundings. However, have you never misinterpreted your body signals? Or ignored or postponed your body needs to catch a deadline or to care for someone else before yourself? A defective relationship with one's own body has been named one of the most frequent symptoms, if not the root of various mental disorders (Khalsa et al., 2018). Distraction from or misinterpretation of one's own body signals oftentimes is related to a decrease in mental or physical health (Brani et al., 2014; Hanley et al., 2017). So, while the body is the ship on which we navigate the world, this ship itself, our body needs, and internal body signals often get out of sync with our behavior. Virtual Reality (VR) offers the possibility of reconnecting with one's body in a novel way. However, even in mental health or therapy-oriented research, little focus has been set on how VR affects body awareness, the attention humans tend to give to their internal body signals.

VR - just a few decades ago, nothing but a vague idea in the minds of some scientists and science fiction authors - has become a realistic possibility today. The much-discussed idea of the *metaverse* represents a concept of how VR could shape our everyday lives and revolutionize our social interactions. While this still appears to be a distant prospect, social VR spaces are flourishing, where people come together, represent and rediscover themselves through diverse virtual characters, and engage in new ways of interacting (Cheng et al., 2022). VR has also already found its way into another area of human life: In therapy. A prominent example of this is phobia therapy (Freitas et al., 2021). For years now, patients have been successfully facing their fears virtually by interacting with virtual spiders (Garcia-Palacios et al., 2002), exposing themselves to virtual heights (Coelho et al., 2009) or giving presentations in front of a virtual audience (Daniels et al., 2020). In addition to these specific behavioral therapy scenarios, various other possibilities for using VR in therapy are being investigated. Whether in physiotherapy (Brepohl & Leite, 2023), in the treatment of chronic pain (Ahmadpour et al., 2019), as part of body image disorder treatment (Riva et al., 2021), or in the context of mind-body or general mental health interventions (Ma et al., 2023), VR with its multitude of design options seems to hold a lot of potential.

As technology evolves, a key feature of VR gains prominence: the embodiment of and interaction with virtual self-representations, so-called virtual bodies or avatars. Having a virtual body can affect how people perceive their body size (Mölbert et al., 2018; Piryankova et al., 2014; Wolf et al., 2022) or their body weight (Kasahara et al., 2017) and even impact their body schema and localization of their body parts (Kilteni, Normand, et al., 2012; van der Veer et al., 2019). These results indicate that the perception of avatars is connected to our body perception and, in some cases, may even override it.

Given the effects of avatars on body perception and the importance of the body in mental disorders, the use of avatars in therapy might hold vast potential for patient health. However, those effects also include some risks. Next to simulation sickness, which is a common short-term risk of VR (Stauffert et al., 2018), the usage of VR can provoke unpleasant sensations of derealization and depersonalization (Peckmann et al., 2022), evoke retraumatization for sexual assault survivors (Porta et al., 2024), or serve as a form of dysfunctional escapism (Han et al., 2022). Regarding body perception, an unforeseen effect on body schema or body weight perception might cause damage to body image. Finally, unforeseen effects on proprioceptive or kinesthetic body perception could affect body awareness, which, in turn, might negatively impact mental health. However, little research has investigated the impact of VR (Heeter et al., 2020), and specifically of avatar embodiment on body awareness.

To bridge this gap, this thesis focuses on exploring the interplay between the degree to which an individual experiences a sense of embodiment towards an avatar (sense of virtual embodiment) and body awareness. It contains seven chapters, not including this summary, examining how different variations of avatar embodiment affect body awareness. In preparation for empirical work, it presents a systematic literature review and a system development report. Across five empirical studies it further explores the relationship between the sense of virtual embodiment and body awareness and gives insights into the effect of discrepancies between the user's corporeal body and their avatar. The results of this thesis indicate the possibilities and risks of using avatars in mind-body interventions. They serve as a basis for the future development of VR-based mind-body interventions.

Chapter 1: Literature Review Chapter 1 contains a literature analysis of research targeting VR mind-body interventions. I used a systematic literature review method to examine how previous work on such interventions considers the participant's body awareness and how they examine potential relationships between typical measures of VR User Experience (UX) and the targeted therapeutic goals. Based on the results, I suggested ways to incorporate both virtual bodies and VR UX into the design and evaluation of VR mind-body interventions.

Chapter 2: System Description Chapter 2 introduces the VR system, which forms the baseline for the following chapters regarding avatar creation and animation, embodiment, and a simple virtual environment modeled after the archetype of psychotherapeutic offices. It includes a UX evaluation of the setup and provides preliminary qualitative insights into the relationship between the sense of virtual embodiment and body awareness.

Chapter 3: Avatar Embodiment and Body Awareness Chapters three to six present four empirical experiments to answer the main research questions. Chapter 3 presents the initial use of the experimental tasks and dependent variables I used in the majority of the studies. The study in this chapter provides insights into the correlative relationship between dimensions of the sense of virtual embodiment and different body awareness assessment methods.

Chapter 4: Effects of VR and a Mirror Perspective Chapter 4 is the first chapter where I elaborated deeper into the effects of creating discrepancy between the corporeal and the virtual body. In this chapter, I examined the effect of replacing reality with virtuality. I compared physical movement exercises performed in a real laboratory to those carried out in a virtual laboratory, which closely mimicked the real one using photorealistic, personalized avatars as virtual bodies. Further, I investigated whether providing more visual information by introducing a mirror perspective enhances or reduces potential effects on body awareness.

Chapter 5: Effects of Avatar Appearance Similarity Chapter 5 approaches appearance discrepancy between the corporeal and virtual body within a virtual environment. In this chapter, I investigated whether appearance similarity has a top-down effect on body awareness and how this effect relates to the effects of appearance similarity on the sense of virtual embodiment. In doing so, I compared photorealistic, personalized avatars to realistic-looking individualized avatars and realistic-looking generic avatars.

Chapter 6: Effects of a Virtual Body Swap Chapter 6 furthers the discrepancy between the corporeal and the virtual body by creating a perspective switch out of the personalized avatar. In this chapter, I introduced a system allowing users to switch their perspective mid-experience to gain a third-person perspective on their photorealistic, personalized avatar. I examined whether such a body swap affects the sense of virtual embodiment, body awareness, and UX. I further tested whether embodying a second avatar in that new perspective (swap avatar) affects the experience and how the sense of embodiment towards this swap avatar relates to body awareness.

Chapter 7: Effects of Body Language Similarity Chapter 7 gives an outlook on follow-up questions, furthering the perspective discrepancy between the corporeal and the virtual body. It introduces a system that allows users to meet photorealistic, appearance-personalized agents showing variable body language. In a pilot study, I showed preliminary effects on the effects of behavior- or personality-similarity on the sense of virtual embodiment. These results indicate a potential use for self-reflective intervention approaches.

Embodiment and Body Awareness in the Context of Mind-Body Interventions

> Orandum est ut sit mens sana in corpore sano.
> [A man should pray for a healthy mind in a healthy body.]
>
> *Juvenal, Satire X, 356*

Over the last 30 years, embodiment has been a repeated and increasing topic in psychological research (Glenberg & Robertson, 2000), philosophy (Clark, 1998; Fuchs & Schlimme, 2009; Shusterman, 1999; Varela et al., 2017), research on artificial intelligence (Pfeifer & Bongard, 2006), and linguistics (Johnson & Lakoff, 2002). The term embodiment is multi-layered and is used variably across these different research fields. In this thesis, I look at the term from a psychological angle and examine its relationship to avatars, mainly focusing on (1) embodiment as a philosophical trend in psychological research, (2) embodiment as a phenomenon of perception and interpretation of one's body, and (3) embodiment as the act of being represented by a virtual body in a virtual environment.

Embodiment as a Philosophical Trend in Psychological Research

In psychology, embodiment, which is also referred to as *embodied cognition* (Wilson, 2002), *embodied mind* (Varela et al., 2017), or *embodied intelligence* (Ziemke, 2013), stands for the trend in research that emerged shortly after the cognitive shift. While the interpretation of the term varies across the different research directions, they have one major common ground: the assumption that psychological processes are influenced by the body and are grounded in a bodily origin (Glenberg et al., 2013). As a trend in psychological research, the term is closely related to philosophical topics that emerged at a similar period, such as somaesthetics and somaesthetic design (Shusterman, 1999).

Behavioral psychological research, as it was conducted at the beginning of the 20th century, treats the mind merely as a black box and a trigger of behavior. Meanwhile, cognitivist approaches emerging in the 1980s view human information processing as strictly separate from physical processes and behavior (Rouse & Morris, 1986). They assume cognition to be amodal, representing and manipulating the external world merely in abstract symbols (Michalak et al., 2012). The introduction of the *embodied mind* by Varela et al. (2017) as a counterpart to this *disembodied mind* brought a new perspective to cognitive processing by considering its relationship to the physical world. Numerous new theories have been developed from this perspective. One of these is the *Grounded Theory of Cognition* by Barsalou (2008). It emphasizes the anchoring of cognition in the brain's modal sensory system and sensory experiences instead of abstract calculations. As a result, psychological embodiment research approaches human experience and behavior comprehensively and holistically, linking different physiological and psychological processes. For example, Glenberg (2010) describes embodiment as a way of unifying psychological research directions. As such, embodiment has relevance in various current psychological fields. On the one hand, the development of abstract cognitive processes can be traced back to physical experiences (Glenberg, 2010). Language and social processes also repeatedly draw on the body, through metaphors and symbols (Michalak et al., 2012) or non-verbal communication cues in body language (Martinez et al., 2016).

Defining the Mind and the Body

What we have learned so far is that embodiment, by these definitions, combines two worlds with each other: The world of the *mind*. And the world of the *body*.

The APA Dictionary of Psychology defines the mind as:

> **mind** n.
> broadly, all intellectual and psychological phenomena of an organism, encompassing motivational, affective, behavioral, perceptual, and cognitive systems; that is, the organized totality of an organism's mental and psychic processes and the structural and functional cognitive components on which they depend. The term, however, is also used more narrowly to denote only cognitive activities and functions, such as perceiving, attending, thinking, problem-solving, language, learning, and memory. The nature of the relationship between the mind and the body, including the brain and its mechanisms or activities, has been, and continues to be, the subject of much debate.
>
> APA Dictionary of Psychology (2018b)

Thus, the mind seems to play a great part in being human. And, as we can see, even the definition of the mind cannot do without referencing its counterpart, the body. The body can also be found as a definition in the APA Dictionary of Psychology. However, compared to the definition of the mind, the definition of the body lacks detail and is shaped in a number of bullet points. The dictionary defines the body as:

> **body** n.
>
> 1. the entire physical structure of an organism, such as the human body.
> 2. the physical body as opposed to the mental processes of a human being.
> 3. the trunk or torso of a human or nonhuman animal.
> 4. the main part of a structure or organ, such as the body of the penis.
> 5. a discrete anatomical or cytological structure, such as the Barr body (see sex chromatin).
>
> APA Dictionary of Psychology (2018a)

In this simple structure, the dictionary merely defines the body as a physical object in the world and (again) as some counterpart to the mind. To obtain a more comprehensive definition that comes closer to what is meant by the body in embodiment research and in this work, I draw upon the theory of *somaesthetics*, a neologism combining the Greek word for body, soma, and aesthetics, which was first introduced by Shusterman (1999). Somaesthetics has found its way into the field of human-computer interaction via somaesthetic design. While Shusterman (2012) refrains from the term *body* to avoid associations with bodily appearance and the merely physical body, he vividly defines the soma. He defines it as a source for bodily subjectivity and sensations: "the soma – the living, sentient, purposive body - as the indispensable medium for all perception" (Shusterman, 2012, p. 3).

The body, therefore, has two sides. On the one hand, there is the body as a physical structure in a three-dimensional space, as an object that we can see, feel and experience. On the other hand, there is the body as a medium of perception, as something that we are and that integrates interoceptive, proprioceptive, kinesthetic, tactile, and spatial information (Schmalzl et al., 2014). So, while embodiment stands for the inseparable connection between body and mind, for the physical basis of cognitive processing, part of embodiment is also the perception of its physical structure (Husserl, 1989; Plessner, 1970).

Regarding the mind, I focused on the narrow definition of the mind to separate the mind and the body. In this work, when mentioning the mind or mental (regarding the mind) states, I intentionally refer to the higher-cognitive part in the continuum between mind and body. Regarding the body, this thesis will focus on its dual structure. On the one hand, I refer to the body as an object, as a physical structure that can be perceived from the outside. For this definition, I use the term *corporeal body*. On the other hand, I will refer to the sensory body, the body as a medium to our perception, the body as a subject. For this definition, I use the term *soma* or *somatic experience*. I use the term *body* in cases where both the corporeal body and the soma play a role.

The term embodiment actively points to the continuum between mind and body, between cognition and perception. The sense of embodiment opens the continuum between perceiving and being perceived, simultaneously being a sensing subject and a corporeal object to be sensed (Wehrle, 2020). It thus mimics the duality of the body in its dual role of somatic and corporeal perception. In this thesis, I use the term embodiment as the sensory baseline for the experience of having a body, leading to the sense of embodiment towards it.

Embodiment as a Part of Self-Perception

Britton et al. (2021) presented a framework of processes involved in self-perception that affect mental health. They align different self-related processes on a continuum between *self-as-object* and *self-as-subject*. Figure 1 gives an overview of their framework. The self-related processes closer to the *self-as-object* describe higher cognitive functions and so-called *reflective* processes of self-perception. The authors refer to these as the *conceptual self-related processes*. They include, for example, the narrative self as an autobiographical identity, including social roles. Further, they include self-esteem, self-compassion, self-criticism, and rumination.

In addition to that, the authors draw a close connection between the *self-as-subject* and so-called *pre-reflective*, or *embodied* self-related processes that describe a person's somatic experience and the perception of their corporeal body. In their definition, this self-as-subject describes first and foremost the perspectival self, the sense that a human's experience is situated from a first-person perspective (Zahavi, 2008), later in this thesis referred to as a sense of self-location. Next to this *minimal self* (Gallagher, 2000), they open up to other embodied self-related processes such as interoception, the processing of internal body signals (body awareness, Mehling et al., 2009), a sense of ownership over the corporeal body (sense of body ownership), a sense of agency with regard to being able to act (Gallagher, 2000), and a sense of boundaries between the body and the world.

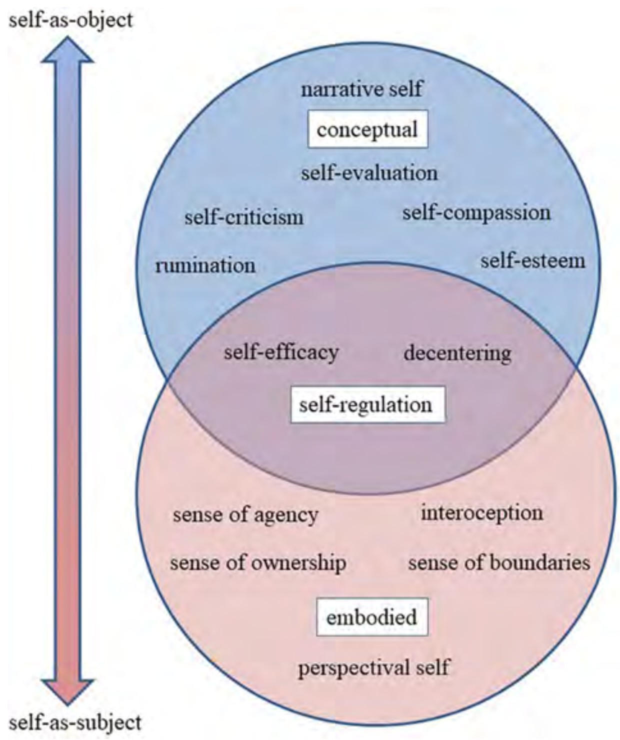

Fig. 1.: Self-related processes on the spectrum between *self-as-object* and *self-as-subject*.
This figure was first presented in Britton et al. (2021) in an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Finally, Britton et al. (2021) present self-regulatory skills as an overlap between embodied and conceptual self-related processes. These allow an individual to de-center and to increase self-efficacy in performing target behaviors.

The self-related processes that Britton et al. (2021) present do not necessarily occur separately but are connected and do interact with each other. An imbalance between conceptual and embodied self-related processing can, therefore, possibly explain a connection to mental disorders. At the same time, their relationship may also clarify the success of mind-body interventions. Psychotherapeutic approaches often focus on shifting the valence of conceptual self-related processes from negative to positive (Beck, 2016) and amplifying self-regulation skills. Given the interactive nature of body and mind, inviting embodied processes, might give additional support, leading to a more holistic approach in tackling mental disorders.

While the framework of Britton et al. (2021) provides a good indication of embodiment in self-perception, it is noticeable that it does not yet fully map the relationship between corporeal body, soma, and mind. The continuum between self-as-object and self-as-subject creates some parallelity to the definition of the corporeal body as a physical object and the soma as a medium for our subjective perception. However, Britton et al. (2021) rather focus on separating higher-cognitive, *reflective* processes and rather perceptual, *pre-reflective* processes without considering the duality of the body and of embodied processes. Thus, for more clarity, in the further parts of this thesis, I will rename the ends of the axis of this framework from self-as-object and self-as-subject to *reflective self* and *pre-reflective self*.

In this thesis, I assign the sense of body ownership to experiencing having a body, and thus to perceiving the corporeal body as an object. The definition of the sense of body ownership induces the consideration of the corporeal body and whether this body as an object is perceived as being in possession of the self. The sense of agency may also be regarded as the processing of the corporeal body in reaction to efferent signals, as it also refers to whether this corporeal body obeys a person's efferent movement commands. On the other hand, the sense of self-location, the sense of boundaries, or body awareness might be sorted into somatic experience. They are closer to the definition of the soma as a medium. Both the sense of self-location and boundaries refer to where a person locates their self in space, not only their body. Additionally, body awareness refers to how a person feels internally without necessarily depicting how this internal body is perceived from an outside perspective. However, these categorizations are not set in stone. For example, internal physical pain can be reduced through a process of *objectification* (Wehrle, 2020) or the sense of self-location can be affected by displaying an artificial corporeal body part from a distorted perspective (David et al., 2014).

Including a distinction between the perception of the corporeal body as a physical object and the soma as a living medium for our perceptions opens up a new question: What happens to embodied self-related processes when the corporeal body changes? In this thesis, I will concentrate on the pre-reflective self, focusing on the interrelation of a sense of body ownership, sense of agency, and body awareness. I explore how the embodied self is affected by virtual bodies as a depiction of visual change of the corporeal body.

Mind-Body Interventions: Embodied Psychotherapy

Following its philosophical development, embodiment has found its way into current approaches in psychotherapy and medicine. Research into body and mind in psychotherapeutic and physical medicine has produced some results that point to a close connection. A vast amount of current research on mental dysfunctions relies heavily on the body, the embodied nature of mental disorders, or the impact of physical experiences on mental health (Glenberg, 2010). Body awareness, in particular, the attentional processing of internal body processes, appears to play a crucial role in mental health, while faulty or inadequate body awareness is inherently related to symptoms of depression or anxiety (Alejandre-Lara et al., 2022; de Jong et al., 2016; D'Silva et al., 2012; Michalak et al., 2012; Paulus & Stein, 2010; Vancampfort et al., 2021).

One branch of therapy that is emerging from embodiment research is *mind-body interventions*, also known as mindfulness-based interventions. In contrast to *mind-body medicine* (Barrows & Jacobs, 2002; Krebs, 2015; A. G. Taylor et al., 2010), which focuses on the potential of the connection between mind and body for physiological healing processes, psychotherapeutic mind-body interventions are a broad field of methods for strengthening positive effects between mind, corporeal body, soma, and behavior to reduce symptoms of mental disorders and increase mental health.

Still and Moved Mind-Body Exercises

Mind-body interventions have been gaining popularity among the general public for their efficacy in the management of mental disorder symptoms (S. B. Taylor et al., 2021). While the usage of the term embodiment in psychological research has only become popular in recent decades, some of its practices and considerations have their origins in long traditions and have always been part of psychological research and investigation (Krebs, 2015). For example, some types of mind-body interventions draw on mindfulness and Buddhist meditation methods that locate consciousness in both the mind and the body. A well-known example of this is the approach of Mindfulness-Based Stress Reduction by Kabat-Zinn (2003) and the associated Mindfulness-Based Cognitive Therapy (Sipe & Eisendrath, 2012).

Mind-body interventions focus attention on the body, leading to increased awareness of body signals (de Jong et al., 2016). While their methods are diverse, mind-body interventions often combine a set of *still* and *moved* exercises. The former are characterized by physical stillness and a mindful focus on the moment, as in mindfulness meditation, or on the body, as in meditative body scans (Khoury et al., 2017). Moved exercises aim to increase body awareness by introducing gentle, repetitive physical exercises and/or breathing techniques, such as those practiced in Yoga or Qi Gong (Niksirat et al., 2019).

As the evaluation of different still and/or moved mind-body exercises is out of the scope of this thesis, I picked an exemplary set of moved exercises from the handbook of Basic Body Awareness Therapy (Gyllensten et al., 2018) which I used as a task in Chapters 3, 4, and 5, and an exemplary still exercise from Self-Compassion Therapy (Neff, 2023), which I used in Chapter 6.

Self-Related Processes as Mediators of Mind-Body Interventions

As the methods of mind-body interventions are very diverse, the research on their effectiveness also varies. However, there is an increasing amount of results indicating their effectiveness in the areas of chronic pain, such as migraines (Wahbeh et al., 2008) or fibromyalgia (Gard, 2005), in anxiety disorders (Paulus & Stein, 2010), as well as in depression (Alejandre-Lara et al., 2022; Paulus & Stein, 2010). Independent of mental disorders, physical exercise can also demonstrably stimulate mental processes and promote mental health (Brani et al., 2014; Fazia et al., 2021; Hanley et al., 2017; Pascoe et al., 2021).

The effects of mind-body interventions can be explained in different ways. While, on the one hand, an effect on optimism and well-being is recognizable (A. G. Taylor et al., 2010), the effects of mind-body interventions can be explained by both top-down and bottom-up processes. Top-down processes are characterized as cognitive processes initiated at the level of the cerebral cortex. In the context of the framework of Britton et al. (2021), these processes would fall under the category of the reflective self and its role in self-regulation. Bottom-up processes, on the other hand, are initiated by somatosensory receptor stimulation, which influences central neural processing through ascending pathways to the brainstem and cerebral cortex (A. G. Taylor et al., 2010). Within the framework of Britton et al. (2021), these processes would fall under the category of the pre-reflective self and the soma's role as a sensory medium in affecting self-regulation.

Various researchers have proposed both top-down and bottom-up processes as important mediators in the evaluation of mind-body interventions (Britton et al., 2021; Desbordes, 2019; Pascoe et al., 2021). While the empirical evidence of this mediating role is variable across the different types of self-related processes (Britton et al., 2021), there exists evidence, that some of them might indeed be crucial in mental health. Khoury et al. (2017) give an overview of top-down and bottom-up effects of both still and moved mind-body exercises. While they mention evidence for the effectiveness of top-down mindfulness meditation exercises for emotion regulation (Chiesa & Serretti, 2010), they highlight the importance of bottom-up processes, emphasizing the role of body awareness. As they pose it, sustained attention to internal body signals can help disengage individuals from dysfunctional cognitive patterns, resulting in a reduction of negative rumination and self-appraisal (Farb et al., 2015).

Focusing on embodied self-related processes, this thesis surrounds body awareness as one of the processes that has been investigated most thoroughly in its effectivity for mental health and which seems to be the main aim in a variety of methods in mind-body interventions, such as top-down oriented body scans, or bottom-up oriented moved practices aiming at a more immediate self-processing and the current moment (Khoury et al., 2017).

Body Awareness: The Conscious Processing of Internal Body Signals

Body awareness is a comprehensive term encompassing the conscious processing of internal body signals. As articulated by Mehling et al. (2011), it refers to the subjective and phenomenological dimension of proprioception and interoception that enters conscious awareness. Thus, it is the conscious perception of bodily states, processes, and actions derived bottom-up from sensory afferents (Mehling et al., 2009). This includes an awareness of both body posture signals (proprioception) and internal somatic signals (interoception), ranging from heart activity to complex perceptive syndromes like relaxation, hunger, or pain. The conscious awareness of these somatic signals is susceptible to modification by various top-down processes, including attention, interpretation, appraisal, beliefs, memories, conditioning, attitudes, and affect (Mehling et al., 2011). Crucially, body awareness goes beyond mere sensory perception. It is inseparable from embodied self-related processing realized through actions and interactions with the environment and the world (Mehling et al., 2011).

One of the most investigated dimensions of body awareness is the operationalization through variables like interoceptive accuracy, evaluated via tasks such as heartbeat counting (Mehling et al., 2009). However, body awareness goes beyond the mere reception of interoceptive body signals by classifying and interpreting them. For this reason, there are also measures that capture body awareness as a self-report. These assess the subjective experience of conscious body awareness, which is closely related to the term *embodied mindfulness* (Khoury et al., 2017). Embodied mindfulness is the notion that mindfulness, “the awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment” (Kabat-Zinn, 2003, p. 145) or the “mental state, including (a) awareness, (b) perceptual sensitivity to stimuli, (c) deliberate attention to the present moment, (d) intimacy or closeness to one’s subjective experience, and (e) curiosity” (Tanay & Bernstein, 2013, p. 1287), is grounded in bodily sensations and encourages the use of embodied practices in mindfulness practice. Body awareness self-report assessments build upon this embodied mindfulness concept. They include assessments of, amongst others, attention regulation (the ability to sustain and control attention to body sensations), body listening (active listening to the body for insight), and noticing body signals (awareness of uncomfortable, comfortable, and neutral body sensations). Further dimensions such as worrying about, distracting from, or trusting body signals and awareness of the body’s role in emotions might be added (Mehling et al., 2018). In this work, I focused on attention regulation, body listening, and noticing body signals[2] and added whether participants paid more attention to visual or non-visual signals. I assessed body awareness within an experience, or post-experience using the State Mindfulness Scale (Tanay & Bernstein, 2013)[3].

The focus of mind-body interventions on consciously processing the body allows for an interpretation of how exteroceptive factors affect dimensions of body awareness and, in turn, how body awareness

[2] In this thesis, I divided these into external and internal signals
[3] German translation by Botrel and Kübler (2019)

might relate to therapeutic goals. In consequence, the therapeutic relevance of interoception, as part of body awareness, has been investigated repeatedly (Britton et al., 2021). The connection between body awareness and well-being extends to both physical and mental aspects. Low or maladaptive body awareness has been consistently linked to symptoms of body image disorders (Braun et al., 2016; Burychka et al., 2021) and is associated with instances of self-harm (Young et al., 2021). In return, various research supports the positive effects of body awareness on mental health. Body awareness has been demonstrated to affect pain management positively (Berry et al., 2020; Datko et al., 2022). Further, Füstös et al. (2012) found that heightened body awareness aids in regulating negative affect. Brani et al. (2014) linked body awareness to subjective well-being, Singer et al. (2004) found empathetic responses, and Cebolla et al. (2016) found a positive relationship to mindfulness. Recent discussions by Gibson (2019) propose enhanced body awareness to be the main contributor to the positive outcomes observed in mind-body interventions. Hence, exploring body awareness contributes to a comprehensive understanding of emotional regulation and underscores its potential therapeutic implications across diverse health domains.

In summary, body awareness encapsulates the multifaceted conscious processing of internal somatic signals. It comprises the duality of being a perceiving soma and having a corporeal body. It shapes an individual's subjective experience of their internal body signals through a complex interplay of mental processes. Finally, it contributes significantly to both individual mental health and the success of mind-body interventions. In this thesis, I focused on body awareness as one of the main embodied self-related processes predicting the success or failure of an intervention design.

Avatar Embodiment: Risks and Potentials for Body Awareness

> As Gregor Samsa awoke one morning from uneasy dreams he found himself transformed in his bed into a gigantic insect. He was lying on his hard, as it were armor-plated, back and when he lifted his head a little he could see his domelike brown belly divided into stiff arched segments on top of which the bed quilt could hardly keep in position and was about to slide off completely. His numerous legs, which were pitifully thin compared to the rest of his bulk, waved helplessly before his eyes.
>
> *Franz Kafka, The Metamorphosis*. Cited from: *Collected stories*, translated by Willa and Edwin Muir.

This opening to the novel *Metamorphosis* by Franz Kafka lays the foundation for the story of Gregor Samsa, a young man living with his parents, who one morning wakes up transformed into an insect-like body. This transformation has various (tragic) effects on Gregor, his self-perception, perception of his surroundings, relationship with his parents, and social environment. With a changed corporeal body and soma, he has to re-learn embodied self-related processes and re-write his conceptual self-related processes while being constantly confronted with the changes in social feedback from his family and in mobility that arise from his new body.

Unthinkable in the physical world, VR makes it possible, at least to a certain extent, to carry out such an embodied self-transformation. Through virtual self-representations that can be shaped at will, users can slip into various roles, take on different virtual bodies, and thus expand their perspective on the world - without the tragic and ultimately fatal consequences that Gregor Samsa is exposed to. But is such a virtual transformation free of consequences? In the next chapters, I will discuss the perception and effects of virtual bodies and options for their use in mind-body interventions.

The Unique Potentials of VR for Mind-Body Interventions

VR has been used in psychotherapy for decades (Riva, 2005). An increasing range of concepts is being developed in the field of mind-body interventions that consider VR as a potential option (Arpaia et al., 2021). Concerning the research on the importance of body awareness in mental health, one major question arises: Can VR strengthen the relationship between mind and body, or does it introduce discrepant information and signals that deflect the focus away from embodied self-related processes?

BehaveFIT: A Behavioral Framework for Immersive Technologies

Wienrich et al. (2021) highlight the potentials of VR for various psychotherapeutic approaches and introduce a framework presenting tools on how to design for psychotherapy and evaluate the potential effects of VR on therapeutic outcomes. Their *Behavioral Framework for Immersive Technologies*, BehaveFIT, provides a structured guide for developing and evaluating VR-based interventions. It focuses on explaining and predicting how these interventions impact therapeutic outcomes, specifically in behavior change processes. This framework offers a concise and theory-based approach to enhance the design and evaluation of VR technologies for effective outcomes.

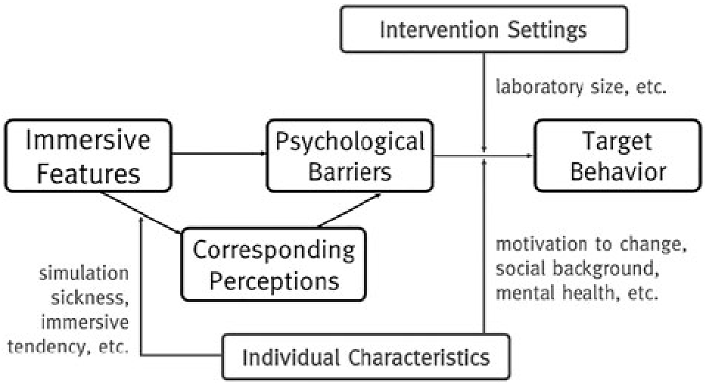

Fig. 2.: BehaveFIT Mediator Model. This figure was first presented by Wienrich et al. (2021) in an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution, or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited in accordance with accepted academic practice. No use, distribution, or reproduction is permitted which does not comply with these terms.

Figure 2 depicts the relationship between BehaveFIT's components. The authors name *immersive features* as a primary source of effects. These describe the components of a VR experience that may impact the desired therapeutic outcomes. In simplified terms, they group these into *self-representation*, *representation of others*, *environment representation*, and *virtual objects*. Self-representation defines the appearance and behavior of a representation of the user within VR, which can, for example, be realized by using a virtual body, a so-called *(self-)avatar*. Representation of others defines the appearance and behavior of virtual others, which, again, might be shown as virtual bodies, either controlled by other human users, *avatars*, or controlled by a computer, *agents*. Environment representation defines the appearance and behavior of the virtual environment, for example, how it reacts to the user's movements and actions. Finally, virtual objects describe the appearance and behavior of interactive objects placed within the virtual environment.

On the opposite side of the framework, Wienrich et al. (2021) name the *therapeutic goals*, which they exemplify as a desired behavior change. To avoid black-box-like testing of the effects of immersive features on the targeted therapeutic goals, the authors introduce two further groups of variables between these two that can be taken into account when designing and evaluating VR-based interventions: first, the *psychological barriers* - i.e., the effects of an intervention on the current state of mind of an individual. The psychological barriers mediate between a therapeutic intervention and a therapeutic goal. Examples of these might be current self-related processes as presented by Britton et al. (2021). Considering the embodied nature of mind-body interventions, it would be appropriate to evaluate body awareness or other embodied self-related processes as a mediator for symptoms of mental disorders.

Inviting VR into an intervention adds a second group of potential mediators for therapeutic effects: VR-specific behavior and perception phenomena. The BehaveFIT framework lists these as *corresponding perceptions* and sets them in the context of each immersive feature. The corresponding perceptions are a group of variables intended to cover the direct responses to signals from the VR experience. They include, for example, the sense of presence in a virtual environment, possibly in combination with the plausibility of the environment (Latoschik & Wienrich, 2022), social presence in the presence of virtual others (Wienrich, Schindler, et al., 2018), and the sense of embodiment toward a self-avatar in the virtual environment (Kilteni, Groten, et al., 2012). Wienrich et al. (2021) attribute a mediatory role to these corresponding perceptions. They assume that the effect of the design of immersive features on psychological barriers is mediated by the different corresponding perceptions or that at least these two groups of variables are related.

While the framework of Wienrich et al. (2021) focuses on fostering behavior changes in the context of behavioral therapy, expanding it to the realm of mind-body intervention could be beneficial to systematically explore the design and research space of VR and self-related processing. In this thesis, I thus apply the framework to mind-body interventions while focusing on the relationship between immersive features, corresponding perceptions, and body awareness as a psychological barrier to the respective therapeutic goals.

Potentials and Risks of VR for Self-Related Processes

Taking the above-mentioned immersive features as a starting point, allows to explore the resulting potential for enhancing self-related processes and, specifically, for increasing body awareness. Based on the four groups of immersive features, there are several possibilities for supporting self-related processes in VR.

In research presenting VR mind-body interventions, the virtual environment is often designed as a nature-like environment, as being in nature is associated with calming and soothing effects (Kaplan, 1995; van Gordon et al., 2018). If the aim of an intervention is, for example, to block out a hectic external environment and thus promote a return to the self and self-awareness (Ahn et al., 2016), having a calming VR environment at hand can be helpful. Another potential of environment representation for self-related processes is the possibility of immersive visualization of biosignals, e.g., based on respiration (Venuturupalli et al., 2019), neural activities (Kosunen et al., 2016), or heart activity (Min et al., 2020). Such a biofeedback scenario enables a playful engagement with one's soma and corporeal body. Virtual objects, such as those incorporating biofeedback, might enhance self-related processes by integrating biofeedback into the virtual environment's design and applying it to interactive objects within the environment (El Ali et al., 2023). The representation of virtual others includes opportunities for enabling conceptual self-related processes. For instance, virtual others emulating the user's actions can serve as a mirror, prompting the user to recognize issues in their behavior. Examples of this can be found in approaches with domestic violence offenders (Seinfeld et al., 2018). Finally, self-representation, and especially the embodiment of a virtual body, has been of particular interest in past research. A variety of studies on avatars has shown the potential of avatar appearance, position, and behavior on self-related processes, such as self-location (van der Veer et al., 2019), body weight perception (Wolf et al., 2020; Wolf et al., 2021), self-distancing (Kross & Ayduk, 2017), or self-compassion and self-counseling (Cebolla et al., 2016; Falconer et al., 2016; Osimo et al., 2015).

In addition to these potentials of VR for self-related processes, there is, of course, always a risk associated with confronting people with a virtual experience. Due to its immersive nature, VR harbors the risk of distracting users from their self-related processes rather than leading back to them. The immersive nature of VR makes it harder to differentiate between real and virtual scenarios, putting vulnerable users at risk of derealization or depersonalization (Peckmann et al., 2022). Moreover, discrepancies between a user and their self-avatar might be associated with some risk for self-related processes. For example, in the area of body image disorders, participants have shown increased dissatisfaction with their corporeal body after being exposed to an avatar with a modified body shape (Porras-Garcia et al., 2019; Preston & Ehrsson, 2018). As another example, the embodiment of avatars with *supernatural* abilities might enhance the perceived weakness of one's corporeal body. Another risk in confronting users with avatars might be experiencing a personalized avatar from an outside perspective. Expectations regarding its behavior or body language might lead to rejection of such a self-representation and, thus, potentially, to conflicts in integrating it into self-related processing.

The Experience of Having Two Bodies

Having and Being a Virtual Body

The immersive feature that strikes most in the context of embodiment, mind-body interventions, and embodied self-related processes is self-representation via a virtual body. As such, it has repeatedly been proposed as a possibility for self-reflection in VR-based therapy (Cui & Mousas, 2023; Osimo et al., 2015). In alignment with the definition of the corporeal body as a perceivable, physical object in space and the soma as a medium of perception (Wehrle, 2020), I define virtual bodies as perceivable virtual objects in the virtual environment, and - in the case of self-avatars - as another medium of perception.

Defining virtual bodies as perceivable virtual objects in the virtual environment is a simple solution. The virtual body represents a person (or a non-human entity) and, as such, is a visible object in the virtual environment. It visualizes social partners and facilitates an interpretation based on their body language (Maloney et al., 2020) or their appearance (Banakou & Chorianopoulos, 2010; Heidicker et al., 2017; Ratan et al., 2019). Self-avatars can be presented from various perspectives (Galvan Debarba et al., 2017). However, they are often placed in the virtual space where the user's corporeal body would be visible from a first-person perspective in the non-virtual space and move in congruence with the movements of the corporeal body. This congruence between the corporeal and the virtual body allows the user to experience the virtual body as a visual object and integrate its processing with other, somatic, signals, such as motor afference or proprioception.

Thus, on the other hand, the virtual bodies' processing might not only consist in the perception of a virtual object but also as a new source of integrated perception and, thus, as a new medium for perception. Of course, in VR, the soma is still the primary medium of our perception. However, empirical evidence has shown that controlling and processing a self-avatar can affect the processing of internal and external signals within a virtual environment. It has been shown that the appearance of an avatar, particularly its skin color, can affect how participants perceive temperature (Kocur et al., 2023). Further, past research revealed that embodied self-related processing can be affected by avatars bottom-up, resulting, for example, in a changed perception of body movements, self-location, or body weight. For example, Kasahara et al. (2017) found that slight temporal deviations and incongruences between avatar and user movements can lead to a feeling of heaviness or lightness on a proprioceptive level. Similarly, van der Veer et al. (2019) found a proprioceptive shift in the orientation of users toward slightly rotated avatar positions. Moreover, the perceived radius of grasping movements can increase depending on the displayed arm length of a virtual body (Kilteni, Normand, et al., 2012). Finally, users tend to re-evaluate their corporeal body weight with regard to avatars of different body sizes (Wolf et al., 2021). Roth and Latoschik (2020) summarize the consciousness of such changes in information processing as a feeling of change in body schema and being changed by the avatar.

As mentioned, there are many ways in which virtual bodies can be present in virtual environments. They can be used as computer-controlled agents that function as *virtual others*, interaction partners, or as a virtual crowd (Palechano et al., 2022). They can be implemented as representations of human users, avatars (Fox et al., 2015), either representing virtual others or oneself. To differentiate between virtual bodies and the body as introduced above, I use the term *virtual body* when referring to avatars or agents, as opposed to the corporeal body of a person's body outside VR.
Breaking down the processing of a self-avatar to whether people perceive it as having or being a virtual body, there is no definite answer. Similarly to the corporeal body and the soma, the processing of the virtual body appears to be a combination of perceiving it as a virtual object and using it as a medium of information about oneself and one's surroundings. However, whether it has the potential to add to the soma as a medium for processing internal body signals, such as body awareness, is debatable.

Sense of Embodiment Toward Virtual Bodies

As a result of the similarity in the definition of virtual and corporeal bodies, the way researchers describe the processing of virtual bodies parallels the processing of corporeal bodies. HCI research on the UX of VR applications often lends terms from psychological embodiment research and modifies them to match the processing of virtual bodies. As a result, research on avatars explicitly focuses on various embodied self-related processes, replacing or extending the embodied self with an embodied avatar. First and foremost, experiencing an avatar from a first-person perspective while controlling its movements is referred to as *avatar embodiment* or *embodying an avatar*. Accordingly, the central concept describing the processing of self-avatars is defined as a virtual sense of embodiment or *sense of virtual embodiment*[4]. Kilteni, Groten, et al. (2012, p. 375) describe this sense of embodiment towards a virtual body as "[The sense that] emerges when [the virtual body's] properties are processed as if they were the properties of one's own biological body", in analogy to the sense of embodiment toward the corporeal body. It describes the merging of avatar processing with self-related processing.

To capture this sense of virtual embodiment, it is usually divided into several dimensions. Kilteni, Groten, et al. (2012) define three main dimensions: sense of *self-location*, sense of *agency*, and sense of *(virtual) body ownership*, making apparent the parallels of avatar processing and embodied self-related processes. Other dimensions of embodied self-related processes, such as the sense of boundaries and body awareness, are mentioned more rarely concerning avatar embodiment or might instead be used as a measure of perceiving the corporeal or somatic body while perceiving the virtual body. In return, they are replaced by processes such as self-similarity or self-attribution (Fiedler et al., 2023) that define how much a user identifies with their self-avatar, or by variables such as change in body schema (Roth & Latoschik, 2020) which defines whether a user perceives changes in their corporeal or somatic experience due to avatar embodiment. In the following, I describe the dimensions of the sense of virtual embodiment presented by Kilteni, Groten, et al. (2012) and the sense of change in body schema proposed by Roth and Latoschik (2020).

Perspectival Self and (Virtual) Sense of Self-Location Kilteni, Groten, et al. (2012) define the sense of self-location as an individual's perception of their spatial existence within a determinate volume in space, similar to the definition of the perspectival self (Britton et al., 2021). The sense of

[4]Over the course of this thesis, I will use the term sense the *sense of embodiment towards [a specified body]* or the term *sense of virtual embodiment* if no specific virtual body is referred to.

(virtual) self-location focuses on the spatial relationship between the perception of self and the virtual body, distinct from the spatial relationship between the self and the environment, which may be part of a feeling of spatial presence and "being there" (Witmer & Singer, 1998) in a virtual environment. Self-location, thus, might be described as the feeling of being inside a (virtual) body. The main factor affecting this sense of self-location might be the perspective in which a virtual body is presented. Typically, a first-person perspective might elicit a matching sense of self-location (Mottelson et al., 2023), while a third-person perspective might provide conflicting information about the position of the self in space and the self in a virtual body.

Sense of Agency - Over a Virtual Body The sense of agency refers to the subjective perception of having control over a body's actions and movements. As it involves the feeling of being the initiator of movements, agency is most notably experienced during exercises that include active motion. Again, this definition is similar for the sense of agency over the corporeal (Britton et al., 2021) and the virtual body (Kilteni, Groten, et al., 2012). The sense of agency arises bottom-up from comparing the predicted sensory outcomes of one's actions, generated from a so-called efference copy (Aoyagi et al., 2021), and the visual feedback of the virtual body. Thus, a primary effector of the sense of agency lies in visuomotor congruence during movements, which can be disrupted, for example, via a sensomotoric mismatch between the corporeal and virtual body. An example of incongruence can be latency between corporeal and virtual body movements (Toothman & Neff, 2019; Waltemate et al., 2016). Other factors, such as the appearance and position of the virtual body, seem to have less effect on the sense of agency (Mottelson et al., 2023).

Sense of Body Ownership - Over a Virtual Body Finally, the sense of virtual body ownership is a major dimension of the sense of embodiment toward virtual or artificial bodies. As mentioned above, it refers to the subjective experience of attributing a body as one's own. It entails a possessive character, where individuals perceive a body as the source of experienced sensations. The emergence of virtual body ownership involves a combination of bottom-up and top-down influences (Kilteni, Groten, et al., 2012), including visuo-motor congruence, and structural or morphological factors such as anthropomorphism.

Sense of Change in Body Schema Interestingly, Roth and Latoschik (2020) introduce a novel dimension of the sense of virtual embodiment, explicitly referring to how users perceive their corporeal body while embodying a virtual body, the sense of change in body schema. The authors highlight the importance of measuring this sense of change in body schema as it goes beyond merely interpreting a virtual body as a temporal part or representation of oneself and assesses the integration of the virtual and corporeal body.

In this thesis, I use the Virtual Embodiment Questionnaire (VEQ) by Roth and Latoschik (2020) to assess the sense of virtual embodiment. It includes three dimensions: sense of virtual body ownership, sense of agency, and sense of change in body schema. For studies that focus on altering self-location via perspective shifts (s. Chapter 6), I additionally assess the sense of self-location using a not-yet-validated scale by Fiedler et al. (2023). This scale includes self-location and more top-down assessments of self-attribution and self-similarity. It has been developed to expand the VEQ to common definitions of the sense of virtual embodiment.

Top-Down and Bottom-Up Effects of Avatar Embodiment

Different top-down and bottom-up processes affect the sense of embodiment towards an artificial body part or an avatar. Various studies have investigated which factors are central to eliciting a sense of virtual embodiment. Regarding the sense of virtual body ownership, the avatar's appearance is part of the top-down processed information, which seems to play a crucial role. Avatars can be designed variously, from highly dissimilar (Cheymol et al., 2023) to photorealistically personalized (Bartl et al., 2021). It has been shown that, to a certain degree, the anthropomorphism of the avatar can lead to an increased sense of virtual body ownership (Latoschik et al., 2017), as does the similarity between avatar and user (Jo et al., 2017; Salagean et al., 2023; Waltemate et al., 2018; Weidner et al., 2023) and the degree of realism (Salagean et al., 2023), potentially increasing its plausibility (Mal et al., 2022). Recent developments in computer graphics allow for the generation of photorealistic avatars that match a person's real-life appearance within a short duration at a low-cost (Achenbach et al., 2017; Bartl et al., 2021). However, avatar personalization can have an influence but is not necessarily a prerequisite for virtual body ownership (Fribourg et al., 2020; Salagean et al., 2023), depending on the user's individual preferences. Other dimensions of the sense of virtual embodiment, such as the sense of agency, are less influenced by these appearance-related factors (Mottelson et al., 2023; Weidner et al., 2023).

Bottom-up, on the other hand, VR users constantly check whether the different signals provided to them by the virtual and the non-virtual environment, by the virtual and the corporeal body, are congruent to each other, either on a visuomotor or a visuotactile level. Early experiments on visuotactile congruence used the rubber-hand illusion, where a sense of ownership over an artificial hand was achieved via congruent visuotactile stimulation (Tsakiris & Haggard, 2005). When embodying avatars, visuomotor congruence, the congruence of the user's and the avatar's body movements, is dominantly used to impact the sense of virtual embodiment with effects on virtual body ownership and agency ratings (Mottelson et al., 2023). Most developments aim at high congruence between virtual and corporeal body movements (Toothman & Neff, 2019; Waltemate et al., 2016). However, it has been shown that slight visuomotor incongruence can affect body perception without risk to a sense of virtual embodiment. One example is the work of Kasahara et al. (2017), who introduced avatars moving slightly in advance to the user, inducing a feeling of being lighter and moving with ease. Another way to create incongruence between signals from the virtual and corporeal body bottom-up is to alter the perspective on the virtual body. The corporeal body is usually perceived from a first-person perspective, occasionally enhanced with a mirror perspective, and, with growing numbers of video calls, with a camera perspective. VR allows for a change in this limited perspective and allows to create virtual out-of-body scenarios (Bourdin et al., 2017; Ehrsson, 2007; van Heugten-van der Kloet et al., 2018), or a third-person perspective on the user's corporeal body (Cebolla et al., 2016). While a virtual body perceived from an outside perspective can elicit a sense of virtual embodiment, little research has been done into how the body movements of such an avatar affect users' perception of it. Further, how such virtual out-of-body experiences affect other, self-related, processes, such as body awareness, has yet to be investigated.

Adding More Than One Self-Avatar

Of course, VR not only allows for introducing one avatar as a virtual self-representation and avatars or agents as a representation of virtual others but also for a range of virtual bodies that combine these or lay in between the self and the other. A variety of research has worked on the concept of controlling more than one avatar at a time (Guterstam et al., 2020), in short, alternating sequences (Verhulst et al., 2022), or of swapping between positions and embodying more than one avatar within one VR experience (Falconer et al., 2016; Osimo et al., 2015; Slater et al., 2019). Including more than one avatar in a virtual environment that might evoke some self-identification or a sense of virtual body ownership or agency over them leads to a new combination of corporeal and virtual body and of virtual self and others. Instead of processing one corporeal body and one virtual body simultaneously, it demands the processing of at least three bodies: two concurring virtual bodies and the corporeal body. Research on embodying two avatars at a time or in close alternations aims at evoking a sense of virtual embodiment, and especially a sense of body ownership and agency over two avatars at a time, resulting in some *dual*- or *multi*-embodiment effects (Guterstam et al., 2020; Verhulst et al., 2022). On the other hand, research on switching bodies within one experience but over a more extended time period is often aimed at self-distancing and self-reflection. For example, Falconer et al. (2016) introduce a swap from an adult virtual body into a childlike virtual body. They report a positive effect on self-compassion. Osimo et al. (2015) and Slater et al. (2019) present a swap from a personalized avatar into an avatar representing a therapist, again reporting a positive impact on self-reflection and self-counseling.

These scenarios have in common that people switch from a body that resembles their corporeal body to a body with a more dissimilar appearance. While they show potential for perspective switches between avatars and for creating out-of-body experiences, how such a swap affects the user's embodied self-related processing and how the concurrent avatars are processed during or after a perspective shift has yet to be examined.

Related Work on Sense of Virtual Embodiment and Body Awareness

There has been some research on the relationship between the sense of embodiment towards an avatar and body awareness. Previous studies found that a person's interoceptive accuracy, thus their ability to detect their heartbeat, can affect how susceptible they are to accept artificial body parts or virtual bodies (Filippetti & Tsakiris, 2017; Monti et al., 2020; Schroter et al., 2023; Suzuki et al., 2013; Tajadura-Jiménez & Tsakiris, 2014) and how susceptible they are to congruent or incongruent stimulation (Filippetti & Tsakiris, 2017). Studies on the *Rubber Hand Illusion* investigate the intricate relationship between body awareness and a sense of embodiment towards artificial body parts, mainly focusing on interoceptive accuracy measures, such as heartbeat counting tasks. Tsakiris et al. (2011) found a negative correlation between interoceptive accuracy and the sense of embodiment toward a rubber hand, indicating a trade-off between internal and external stimulus processing, later replicated by Schauder et al. (2015). Filippetti and Tsakiris (2017) investigated the effects of visuotactile congruence on the sense of virtual embodiment and interoceptive accuracy in a Rubber Hand Illusion, with positive impacts of congruence on both variables. Their study further demonstrates that embodiment can potentially increase interoceptive accuracy, particularly for individuals with initially low performance. However, in a study where users embodied an artificial face, they found negative effects of visuotactile congruence, particularly for individuals with higher initial interoceptive accuracy.

Regarding self-reported body awareness, David et al. (2014) did not find an effect of body awareness in daily life on susceptibility to feeling a sense of embodiment towards an artificial hand, while Dewez et al. (2019) found a descriptive, but no significant relationship.

Existing research indicates associations between interoceptive accuracy and sense of virtual embodiment and some relationship between self-reported body awareness and sense of virtual embodiment. However, significant research gaps persist, particularly in understanding the effects of VR on subjective self-ratings of body awareness. Heeter et al. (2020) indicate a positive association between self-reported body awareness and presence in a virtual environment. However, they did not include virtual bodies. Studies on self-reported trait body awareness scales and sense of virtual embodiment have yielded mixed results (Cebolla et al., 2016; David et al., 2014; Dewez et al., 2019). However, they did not include a state measure of body awareness during or after the experience. Potential adverse effects of sense of virtual embodiment on body awareness could limit the effectiveness of VR in mind-body interventions. In this thesis, while still recording an interoceptive accuracy measure, I focussed on self-rated subjective body awareness during and after the experience. In a series of studies, I tested the effects of different avatar embodiment scenarios on this state of body awareness. I established a relationship between body awareness, the sense of embodiment towards one's corporeal body, personalized, photorealistic virtual avatars and agents.

In summary, VR facilitates novel bodily experiences by confronting users with virtual bodies that differ in appearance, size, body shape, movement, perspective, or number from the user's corporeal body. So far, the research on avatar embodiment has mainly focused on how different top-down or bottom-up information about an avatar affects the sense of virtual embodiment. An investigation of how these affect self-related processes, such as body awareness, is still largely unexplored. In this work, I focused on personalized self-avatars representing the user in the virtual environment while partly including self-avatars with different appearances (Chapter 5), avatars representing virtual others (Chapter 6) and outside perspectives on one's personalized avatar (Chapters 6, 7) while being confronted with non-personalized avatars from first-person perspective. To bridge the gap in former research, I examined the sense of virtual embodiment for two virtual bodies - and the effects of perspective changes and having a second avatar on embodied avatar- and self-related processing. Finally, I explored how the perception of a personalized avatar changes when its body language differs from that of the user (Chapter 7).

A Framework of Self- and Avatar-Related Processes

Avatar embodiment describes a situation where the user is confronted with having two bodies, one corporeal and one virtual, that integrate into their self-related processing and may contain contradictory information. To allow for a visualization of this duality, I propose an expansion of the framework of Britton et al. (2021) by a new dimension between the two poles *corporeal body as an object* and *virtual body as an object*[5]. Figure 3 gives an overview of this expanded framework with a possible categorization of avatar-related processes. While this framework does not claim full comprehensiveness, it gives an overview of how adding a second, virtual, body to a system might affect self-related processes.

Concerning the pre-reflective self in the bottom half of the figure, this new framework allows for a comparison and a differentiation between embodied self-related and embodied avatar-related processes. Internal processes, such as body awareness, are uniquely placed within embodied self-related processes. Other self-related processes, such as agency and body ownership over the corporeal body, are mirrored by agency and body ownership over the virtual body. While agency or body ownership over either of the two bodies might be processed simultaneously and related to each other, they are separate processes that mainly cover how a user perceives the two bodies as objects. However, some processes symbolize an integrated perception of the virtual and corporeal body. They fall into the overlapping category *integrated embodied self-processing* within the framework. These processes include, for example, self-location or change in body schema, which are realized in VR through the integration of virtual and corporeal body position and posture (Kasahara et al., 2017).

However, In addition to this embodied avatar processing, avatars are also processed on a reflective level. At the level of the reflective self, the new dimension allows for the addition of *conceptual avatar processing*, which includes, for example, more top-down oriented processes such as self-similarity or self-attribution with an avatar based on its appearance. Top-down processing of the appearance of a self-avatar plays a unique role in VR research. Depending on the size of the avatar (Yee & Bailenson, 2007), its gender (Banakou & Chorianopoulos, 2010) or its racial identity (Ash, 2016), people adapt their behavior in social VR according to their reflected expectations. This leads to a so-called Proteus effect (Yee & Bailenson, 2007). An overlap with the conceptual self-related processes could further explain such effects, in which the boundaries of conceptual self-perception seem momentarily softened by the avatar's appearance (s. Figure 3, *integrated conceptual self-related processes*). Finally, the framework introduces overlap between conceptual and embodied avatar-related processes: *intermediate avatar-related processes*. This category includes processes that might be attributed to both reflective and pre-reflective processes, as in the experience of body ownership over a virtual body, which combines top-down and bottom-up information processing (Mottelson et al., 2023).

Using this framework, introducing a second (self-)avatar to the scenario would add a third dimension, allowing for separate and integrated processing of both avatars and the user's corporeal body. As humans only have a certain amount of capacity for information processing, processing one or more virtual bodies, thus, may concur with processing one's corporeal body and soma (Mejia-Puig & Chandrasekera, 2023, 2022). The processing of external signals, such as proposed by avatar embodiment, may compete with the processing of interoceptive signals, potentially posing constraints on body awareness. As a solution, leveraging visuotactile or visuomotor congruence in the embodiment of artificial bodies might be a strategy to not only increase the sense of virtual embodiment towards a

[5]Again, keeping in mind that the embodied processes not only concern the corporeal and virtual body but are related to and mediated by the soma.

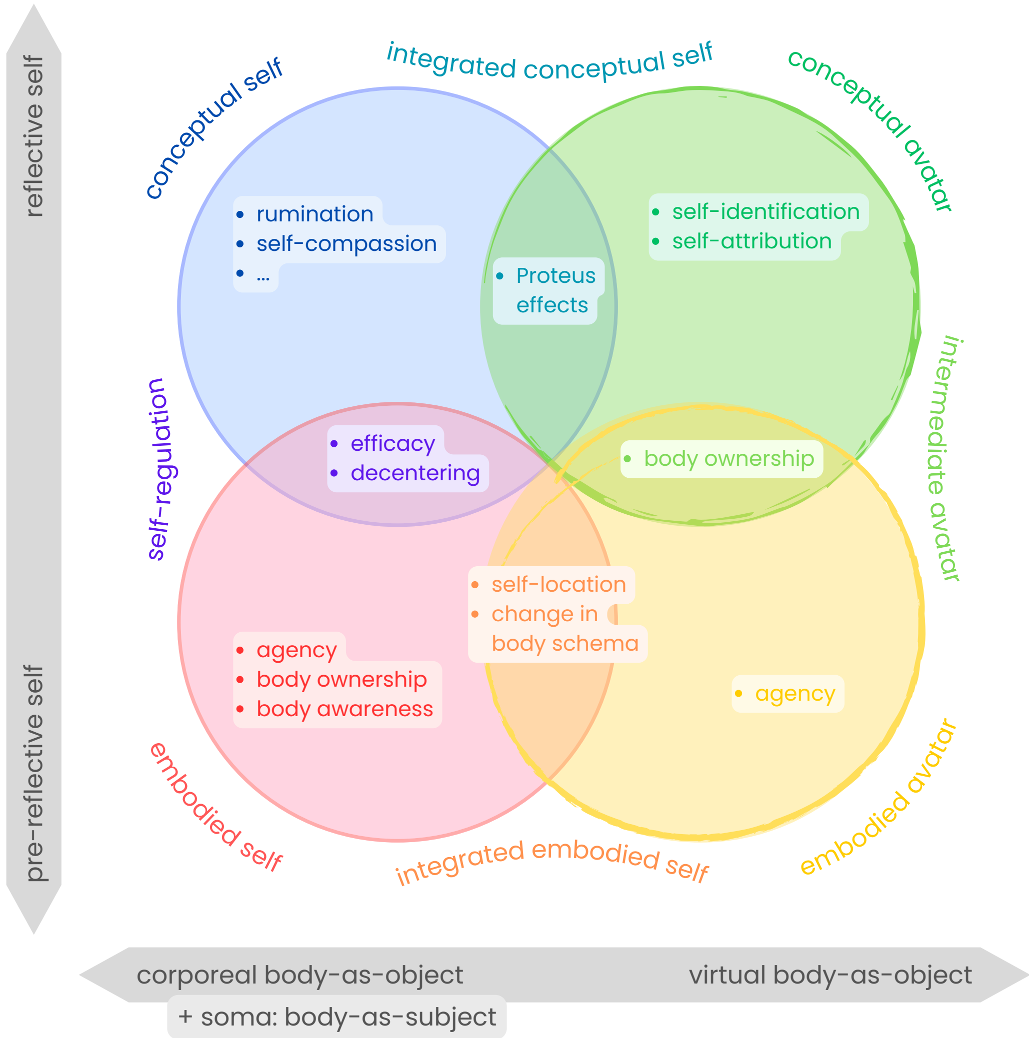

Fig. 3.: Framework of self- and avatar-related processes during avatar embodiment. Adapted and expanded from Britton et al. (2021). Each area symbolizes a category of self- or avatar-related processes.

virtual body but also to maintain or enhance self-related processing such as body awareness (Filippetti & Tsakiris, 2017; Tsakiris et al., 2011).

To summarize, there are strong parallels between avatar- and self-related processing. Research suggests that, while some processes are separate, the signals from the virtual and the corporeal body are somehow integrated. In this thesis, I mainly focused on the lower half of the framework and the interplay between embodied self-related processing, embodied and intermediate avatar processing, and integrated embodied self-processing.

Research Questions

The intricate interplay between the mind and the body and the dual nature of being perceived (corporeal body) and perceiving (soma) underscores the complexity of human experience. Mind-body interventions focus on this interplay and highlight the effects of embodiment in psychological research and therapy. Existing research supports the effectiveness of these interventions and stresses the importance of body awareness as a mediating factor. The introduction of avatars in VR-based mind-body interventions adds an interesting twist. Avatar-related processing reflects self-related processing and seems to have the potential to affect how we feel in a virtual, corporeal, and somatic body. However, there is a lack of research regarding the converse effect of VR and especially of avatars assigned to a user on body awareness. Specifically, exploring how discrepancies between a user's virtual and corporeal bodies affect body awareness could be crucial in designing VR mind-body interventions and in understanding how humans experience themselves within a virtual environment.

This work contributes to the knowledge of VR's impact on the human body as an information provider and basis for mental health. Specifically, I look at the relationship between the sense of embodiment that individuals attribute to a personalized, photorealistic avatar and body awareness.

In a series of projects, I investigated three main research questions (RQ): In a scenario with an embodied, photorealistic self-avatar and simple movement practice...

RQ 1: Which dimensions of the sense of virtual embodiment are related to body awareness?

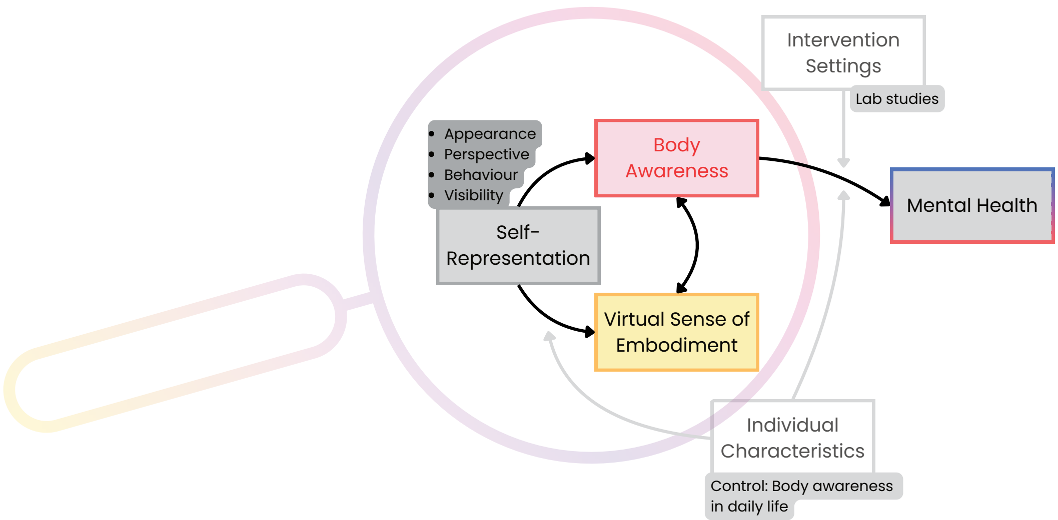

Fig. 4.: Overview of the examined variables and classification in the structure of the BehaveFIT framework. The focus of this thesis is the left side of the framework: the relationship between self-representation, sense of virtual embodiment, and body awareness.

Figure 4 gives an overview of the variables explored in this thesis, following the structure of the BehaveFIT framework (Wienrich et al., 2021). As independent variables and *immersive features*, I focused on avatars as a form of virtual self-representation. Throughout this thesis, I varied the avatars' appearance, the users' perspective on a personalized avatar, the avatars' visibility, and their body language. The theoretical *target behavior* can be replaced by mental health or by reducing symptoms of different mental disorders. However, the research in this thesis focuses on a step before the target behavior, namely on the relationship between *corresponding perceptions* of avatar embodiment and of the *psychological barriers* to this target. As a corresponding perception, I primarily focused on the sense of embodiment towards the respective avatar, assessed in-VR via individual items (Appendix A) and post-VR via the VEQ (Roth & Latoschik, 2020). For the psychological barriers, I focused on body awareness, assessed in-VR via individual items (Appendix B) or post-VR via the State Mindfulness Scale (Tanay and Bernstein, 2013). Finally, I controlled for individual characteristics, especially for the users' body awareness in daily life, using the Multidimensional Assessment of Interoceptive Awareness, Version 2 (MAIA 2; Mehling et al., 2018) and their ability for interoceptive accuracy, using heartbeat counting tasks (Desmedt et al., 2020).

The empirical studies of this thesis represent a variety of discrepancies between the virtual and the corporeal body. First, I investigate how replacing the visual information about the corporeal body with a photorealistic personalized avatar and a mirror perspective affects body awareness. I then increase the discrepancy between the virtual and corporeal body by (a) reducing appearance similarity, (b) shifting perspectives out of the personalized avatar, or add another layer by (c) shifting into a different, non-personalized avatar, that (d) behaves similarly or dissimilarly to the user's body language. Based on the results, I make an assumption about whether the use of personalized virtual avatars represents an opportunity or a risk for the use of VR in mind-body interventions and to what extent an increased discrepancy to the corporeal body can be beneficial.

I limited this thesis to virtual scenarios targeting self-reflection, including soft, repetitive movement practices derived from Basic Body Awareness Therapy (Appendix C; Gyllensten et al., 2018) or a guided self-compassion meditation (Appendix D; Neff, 2023) as a baseline for VR-based mind-body interventions. I further limited it to photorealistic, personalized avatars as the user's representation in the virtual world as opposed to the wide variety of possible avatars. Finally, this thesis focuses on VR systems that foster a high level of bottom-up visuomotor congruence between the user's movements and their avatar's reactions. In doing so, I assume a well-functioning system, which I see as a basic requirement for the usage of VR in therapy as it allows for increased presence in the virtual environment (Souza et al., 2021) and avoidance of aversive outcomes like simulator sickness (Stauffert et al., 2018). In return, some scenarios are out of the scope of this work. These include for example, scenarios with more complex interactions (social or non-social), scenarios in different virtual environments, including nature or more abstract environments, scenarios with non-personalized avatars, and scenarios in less-immersive systems, such as augmented reality. While these may require investigation in future work, they are only discussed peripherally in this thesis. I discuss potential relationships and provide an outlook on possible follow-up work.

Ethical Concerns

Investigating mental health-related variables such as body awareness in VR raises ethical concerns. First, an in-depth engagement with the body entails the risk of drawing attention to feelings of dissatisfaction with one's corporeal body. For example, in the context of body image disorder, this could trigger unwanted negative thoughts. A risk factor for this could be the mirror confrontation with a personalized, photorealistic virtual body (Veale & Riley, 2001). Moreover, meditative mind-body exercises can also trigger negative thoughts and perceptions (Farias et al., 2020). To minimize this risk, the participants were informed in advance that the studies would focus on the body. Individuals with body image disorders were excluded from participation, and information about support services was provided as part of the study information.

Personalized Photorealistic Avatars: Privacy A second ethical concern in this thesis might be the use of photorealistic personalized avatars. These are considered sensitive data, which not only enables but also increases the likelihood that study data may be traced back to a participant. To prevent traceability, I recorded the avatar data (pictures and avatars) separately from other study data and stored them using a separate access code.

Personalized Photorealistic Virtual Bodies: Intimacy Thirdly, the use of personalized photorealistic virtual bodies raises another ethical issue: The control and embodiment of the personalized avatar by another person, as presented in Chapter 6. An avatar does not necessarily equal one's corporeal body and there is no direct physical proximity when another person embodies it. However, the high level of identification with a personalized photorealistic avatar could lead to a perceived invasion of privacy. In addition, the body image disorders mentioned above may involve further unknown risks with regard to self-perception in a body swap scenario. To minimize this risk, all participants were informed in detail before the study in Chapter 6 that another person would control their personalized avatar and see it from a first-person perspective. They were instructed to refrain from participating if they felt uncomfortable with this idea. Additionally, I provided information on support services in the participant information.

General Issues in VR Finally, an ethical concern that all studies with VR have in common is the possibility of simulator sickness. Simulator sickness manifests as discomfort caused by the VR environment, including nausea, balance problems, or vomiting (Kennedy et al., 1993). Several factors were taken into account to reduce the risk of simulator sickness. The studies were conducted on high-end computers with state-of-the-art VR head-mounted displays. Care was taken to maintain a low system latency and minimize sudden movements or movements not performed by the participants. Finally, participants were instructed to discontinue participation in the study at the slightest sign of discomfort.

The Institute for Human-Computer-Media ethics committee at the University of Würzburg[6] reviewed all studies and found them ethically unobjectionable.

[6] https://www.mcm.uni-wuerzburg.de/forschung/ethikkommission/

Chapter Overview

Chapter 1: Literature Review

Title Challenges and Opportunities of Immersive Technologies for Mindfulness Meditation: A Systematic Review

Topic In this chapter, I performed a systematic literature review to examine whether previous work on VR-based mindfulness applications has considered the body of the participants and suggest ways to incorporate it into the design and evaluation of Vitual, Augmented, and Mixed Reality (VR, AR, MR; in short: XR) interventions.

The review targets the following research questions:

RQ 1: What are the differences in the research of XR-based mindfulness support compared to the broader field of HCI mindfulness research?

RQ 2: Which VR features are used in current research on XR-based mindfulness interventions?

RQ 3: Which type of guidance, feedback, and tasks are included in current XR-based mindfulness support, and do they support embodied mindfulness?

RQ 4: What are the effects of XR design on corresponding perceptions and mindfulness?

Methods Following PRISMA (Moher et al., 2011) guidelines, I conducted a systematic literature review of papers published between January 2010 and October 2020. I used the term ["mindfulness" OR "mindful" OR "meditation" OR "meditative"] AND ["virtual reality" OR "VR" OR "augmented reality" OR "AR" OR "mixed reality" OR 'MR" OR "XR" OR "immersion" OR "immersive"] in the following databases: *ACM Digital Library* and *U.S. National Institutes of Health's National Library of Medicine (PubMed)*. Inclusion criteria for the analysis of RQ 1 to 3 were: (a) focus on mindfulness or mindfulness meditation, (b) presentation or evaluation of an XR system and (c) focus on novel development and/or an empiric study. In addition, to answer RQ 4, I defined PICOS (Methley et al., 2014) criteria for effect evaluation.

Main Results The main results of my review were as follows. Compared to the diverse studies on mindfulness in human-computer interaction, I found a very limited focus within the field of XR research. Most papers centered around the therapeutic and calming effects of VR mind-body interventions (RQ 1). With regard to specific VR features (RQ 2), following the BehaveFIT framework (Wienrich et al., 2021), most of the literature focused on nature-inspired scenarios (environment representation) and did not include interactive objects (virtual objects), virtual others (other representations) or a virtual self-representation. Regarding guidance and feedback (RQ 3), most literature focused on guided meditations with vocal instructions. Some included biofeedback or other tasks. Finally (RQ 4), the studies evaluating the effects of VR interventions mainly focused on comparing VR and non-VR interventions. They revealed mixed results, mostly indicating no significant difference between conditions. While most of the studies did not test for VR corresponding perceptions such as a sense of presence or a sense of virtual embodiment, I found some indications for a positive effect of these on mindfulness and therapeutic outcomes. With regard to body awareness, the studies included in this review that focused on virtual bodies found some indication that VR did not lower body awareness compared to non-VR interventions.

Contribution This chapter contributes valuable insights into the current state of XR-based mindfulness research, identifies gaps, and proposes a structured framework for designing and evaluating XR-based mindfulness support. The findings suggest opportunities for enhancing XR interventions and emphasize the importance of exploring interactive and embodied elements for more effective outcomes.

Based on the results, I adapted the framework of Wienrich et al. (2021) to the topic of mind-body interventions. I extracted three elementary steps in evaluating a VR mindfulness task: the intervention objective, the factors to be considered in task design, and the variables to be considered in evaluation. The proposed framework provides a structured approach to addressing current research gaps and enhancing the effectiveness of XR mind-body interventions.

Chapter 2: System Description

Title Resize Me! Exploring the User Experience of Embodied Realistic Modulatable Avatars for Body Image Intervention in Virtual Reality

Topic This chapter presents the development and evaluation of the VR system I used as a baseline system for all my studies. The system components include creating personalized virtual bodies, a tracking system, and a unity-based avatar animation retargeting system. As the system in this chapter was developed specifically to target body image disturbances, it includes the possibility to actively modify the avatars' body weight in real-time, which is not part of the other studies in this thesis.

Next to the system description, the chapter includes a user evaluation with 12 participants, evaluating security, physical comfort, accessibility, usability, and user experience via quantitative and qualitative assessments. It specifically focuses on the potential of VR technology, using personalized avatars to support interventions aimed at improving body image in the context of obesity. With regard to the topic of my thesis, this study examined the following research questions:

RQ 1: How can a VR system enable users to embody a photorealistic, personalized avatar within a virtual environment?

RQ 2: What is the user experience during personalized virtual body generation and interactive VR exposure, with regard to security, physical comfort, presence, simulator sickness, and avatar perception?

RQ 3: How does the embodiment of a photorealistic, personalized avatar affect the subjective experience of body awareness?

RQ 4: What are the implications for designing and developing avatar-based (body image) therapy support tools?

Disclaimer The system components presented in this chapter include the process of creating personalized virtual bodies which were used in all of my studies, the unity-based avatar animation retargeting system I used in Chapters 3, 4, 5, and 6, and the tracking system I used in Chapters 3 and 4. In Chapters 5 and 6, I used a different tracking system by Captury (2021) which is explained in Chapter 5. The system in Chapter 6 additionally adds to the system by allowing for a multi-user integration. The system in Chapter 7 differs from the other systems as it was implemented in Unreal game engine.

Method The study in this chapter uses a mixed-method approach. The procedure is exemplary for the rest of the studies conducted in this thesis. Participants performed a simulated therapy appointment in which their corporeal body was scanned to create a personalized, photorealistic virtual body. Following this, body measurements were taken, and the participants were prepared for the VR experience. The first step in VR was to check whether the participants could see clearly. The embodiment system was calibrated, and the participants performed a few movement exercises in front of a mirror to increase their sense of virtual embodiment (Waltemate et al., 2018). They then performed exercises associated with the respective therapeutic context, in this study, changing their avatar's body size. Participants were asked about their current state of mind in qualitative interviews at various times. In addition, they answered qualitative and quantitative questions on the above-mentioned variables, their body awareness, and the sense of embodiment towards their virtual body.

Main Result This UX study exemplifies a process that provides comfort to participants during personalized avatar creation and a VR scenario, including avatar embodiment (RQ 1). While some participants reported slight sensations of discomfort or insecurity during the avatar creation process, the overall UX of the processes and the VR experience were rated positively (RQ 2). The study provides some initial insights into the connection between body awareness and a sense of embodiment toward a personalized, photorealistic virtual body, indicating a lower body awareness during more movement-related tasks. Some participants claimed effects on their body awareness during the process, which differed widely between them, from feeling distracted by their avatar to experiencing focus on their soma during avatar embodiment. Finally, one of the main results of this study is its design guidelines for future VR-based therapy systems (RQ 4) that form a baseline for further development.

Contribution The paper contributes to the knowledge of VR therapy by presenting the development and evaluation of a VR system designed to support body image interventions. This chapter introduces a VR system that allows users to embody a photorealistic, personalized virtual body within a virtual environment and enables users to modify their avatar's body weight in real-time. It presents an extensive user experience evaluation of the VR system, including a formative evaluation of the avatar generation process and interactive VR exposure with a small sample of healthy participants, including security, physical comfort, usability, and user experience. This comprehensive assessment helps identify areas for improvement and informs the development of design guidelines for future VR systems supporting body image interventions. Finally, this chapter reveals insights into the subjective experience of body awareness during avatar embodiment. It presents a set of guidelines for the future design and development of similar avatar-based therapy support tools. These guidelines aim to enhance therapeutic VR interventions' effectiveness, usability, and user experience.

Chapter 3: Avatar Embodiment and Body Awareness

Title Virtual Reality for Mind and Body: Does the Sense of Embodiment Towards a Virtual Body Affect Physical Body Awareness?

Topic In this chapter, I investigated how the sense of embodiment toward a virtual body and body awareness are related using fully embodied, personalized avatars. In a study with 24 participants, I examined whether the sense of embodiment relates to body awareness aspects, namely self-reported body awareness and performance in a heartbeat counting task. Using personalized virtual bodies, the chapter tackles the following research questions:

RQ 1: Does a trait in body awareness predict the impact of a VR body awareness exercise on the state of body awareness?

RQ 2: In a VR body awareness exercise, does the sense of embodiment toward a virtual body relate to body awareness?

RQ 3: Does the perceived eerieness of a virtual body affect body awareness?

Method Using the same preparation processes as in Chapter 2, 24 participants embodied a photorealistic, personalized virtual body while repeatedly performing simple in-VR body awareness tasks in front of a virtual mirror. The exercises were derived from Gyllensten et al. (2018) and are repeatedly used in the following chapters. As an assessment of body awareness, we implemented a heartbeat counting task, based on the work of Schandry (1981) and self-reported in-VR and post-VR ratings, based on the State Mindfulness Scale (Tanay & Bernstein, 2013) which were used in all chapters except Chapter 7. For the assessment of the sense of virtual embodiment, we used self-reported in-VR and post-VR ratings based on the VEQ (Roth & Latoschik, 2020).

Main Result This study revealed a positive effect of the trait in body awareness on state body awareness ratings but not on heartbeat counting performance (RQ 1). It further revealed an intrapersonal relationship between a sense of virtual embodiment and body awareness, especially regarding sense of virtual body ownership and a sense of agency over an avatar, again for self-reported body awareness but not for heartbeat counting performance (RQ 2). Finally, the study revealed a tendency but no significant relationship between perceived humanness and attractiveness of a personalized avatar and body awareness ratings, but not for perceived eerieness (RQ 3).

Contribution The contribution of this chapter is twofold: It provides insights into the relationship between avatar perception, namely a sense of virtual embodiment and perceived uncanniness of the virtual body, and several measures of body awareness. It initiates a conversation toward a systematic evaluation of the effects of virtual bodies on body awareness.

Chapter 4: Effects of VR and a Mirror Perspective

Title Are Embodied Avatars Harmful to our Self-Experience? The Impact of Virtual Embodiment on Body Awareness

Topic In this chapter, I examined the effects of a VR experience that is as close to reality as possible on body awareness. The embodiment of avatars in virtual or real environments involves a complex combination of virtuality and reality: the corporeal body is visually replaced by a virtual body, the movements of which are, in turn, controlled by corporeal body movements. This chapter tackled the following research questions:

RQ 1: Does embodying a personalized, photorealistic virtual body in VR affect body awareness compared to performing the task in a corporeal laboratory environment?

RQ 2: Does the sense of embodiment towards one's virtual body in VR differ from the sense of embodiment towards their corporeal body in a corporeal environment?

RQ 3: How does an additional mirror perspective affect body awareness in corporeal and virtual environments?

RQ 4: How does an additional mirror perspective affect the sense of embodiment?

RQ 5: To what extent does the sense of embodiment towards a virtual body mediate the effects of perspective or virtuality on body awareness?

Method In a 2×2 mixed design, 44 participants performed body awareness exercises in reality and in a virtual lab configured to look the same as the real lab with a personalized, photorealistic virtual body as self-avatar (Virtuality: within-subjects factor). They performed the exercises in front of a mirror, or not (Perspective: between-subjects factor). The procedure in this paper adapts to the method in Chapter 3.

Main Result The findings revealed that virtuality negatively affected body awareness (RQ 1) and the sense of embodiment toward the visible (corporeal or virtual) body (RQ 2) and that having a mirror perspective shifted the attention from somatic to visual signals (RQ 3) but did not significantly affect the sense of embodiment (RQ 4). When calculating the relationship between the sense of embodiment toward the visible body and body awareness, we found that the effects of virtuality on body awareness depended on the sense of embodiment towards the virtual body (RQ 5). A sense of change in body schema increased the attention toward visual instead of somatic signals and decreased the noticing of internal body signals. A sense of agency led to an increase in attention regulation.

Contribution This chapter provides new insights into the perception of this interplay of virtual and corporeal signals. By using photorealistic images of the users and the environment, the findings clearly emphasize the effects of VR on the sense of embodiment over the body that is currently visible (corporeal or virtual body). Even in a virtual environment with strong anchoring in the physical environment with photorealistic avatars modeled on the users, the medium of VR affects body awareness. The effects of an additional confrontation with a (virtual) mirror image and the interplay of the triggered sense of embodiment with body awareness towards the corporeal body form a basis for several further research questions in the field of embodiment and avatar interaction. The work thus offers important insights into the interplay of avatar and body perception that are highly relevant to human-computer interaction.

Chapter 5: Effects of Avatar Appearance Similarity

Title If It's Not Me It Doesn't Make a Difference – The Impact of Avatar Personalization on User Experience and Body Awareness in Virtual Reality

Topic In this chapter, I examined whether body awareness in a VR system depends on the appearance of one's avatar, in particular, on the customization or personalization of the virtual body. I further investigated how body awareness relates to the sense of virtual embodiment and other VR-specific responses, referred to as VR UX. Previous work suggests that higher similarity between the user and avatar increases the sense of virtual embodiment. Having shown in my previous studies that sense of virtual embodiment is positively related to body awareness in personalized avatars, I now investigated to what extent the relationship between sense of virtual embodiment and body awareness differs between personalized, customized and non-personalized avatars. The study in this chapter investigated the following research questions:

RQ 1: Does the degree of individualization of an embodied avatar impact body awareness and VR UX in a VR mind-body exercise?

RQ 2: Does VR UX affect body awareness?

RQ 3: Does the degree of avatar individualization impact the relationship between VR UX and body awareness?

Method In a 3×1 between-subjects design, 86 participants performed body awareness exercises in VR, either embodying a realistic-looking, generic virtual body, a realistic-looking customized virtual body which they picked from a set of possibilities, or a personalized, photorealistic virtual body as in the previous chapters. They rated their sense of embodiment toward the avatar, body awareness, simulator sickness, an uncanny valley effect, and presence.

Main Result While customization had close to no effect or even a negative effect, personalization had a positive effect on the sense of virtual embodiment (RQ 1). However, personalization led to an increased feeling of eeriness and reduced body awareness (RQ 1). Again, we found a positive relationship between sense of virtual body ownership and agency and body awareness, but not regarding the sense of change in body schema (RQ 2). However, this relationship was not affected by the avatar's appearance (RQ 3).

Contribution This study deepens the understanding of how avatar design influences body awareness in therapy within VR. It highlights the balance between customization and personalization in therapeutic contexts by comparing different avatar types. The findings show that while customization did not significantly affect body awareness, personalized avatars reduced it while increasing sense of virtual body ownership and uncanny valley effects. Understanding these dynamics is crucial for designing effective VR interventions, especially in therapy. To optimize for therapeutic outcomes, finding a balance between avatar design, sense of virtual body ownership, and body awareness is crucial.

Chapter 6: Effects of a Virtual Body Swap

Title Virtual Body Swapping: A VR-Based Approach to Embodied Third-Person Self-Processing in Mind-Body Therapy

Topic In this chapter, I investigate the role of the interplay between sense of virtual embodiment and body awareness within a possible application scenario in mind-body interventions: a VR-based self-compassion meditation.

Self-compassion, i.e., the loving treatment of one's weaknesses and painful experiences (Neff, 2003), is, like body awareness, an essential component in the psychotherapeutic treatment of various disorders. Many exercises in self-compassion therapy involve the body, either through self-touch, body journeys, or body movement exercises. To represent the loving view of the self in virtual space, this chapter presents a system in which people can leave their virtual self behind and perceive it from an outside perspective. As part of the evaluation of this method, I investigated how leaving one's personalized avatar affects body awareness and sense of virtual embodiment and whether taking on a first-person perspective on a new avatar amplifies such an effect. The study in this chapter investigated the following research questions:

- RQ 1: Does a virtual body swap affect the sense of embodiment toward a personalized self-avatar?
- RQ 2: Does the visibility of a swap avatar affect the sense of embodiment toward the personalized avatar?
- RQ 3: Do participants experience the sense of embodiment toward a non-personalized swap avatar while their personalized avatar is visible in the same virtual space?
- RQ 4: Does a virtual body swap affect self-related processes?
- RQ 5: Does the visibility of a swap avatar affect self-related processes?
- RQ 6: In body swapping, how does the sense of embodiment toward a personalized avatar relate to self-related processes?
- RQ 7: How should a virtual body swap scenario be designed to elicit a positive UX?

Methods The study employed a 2×2 mixed design, wherein all participants initially embodied their personalized avatar before the body swap. In each session, they rated their sense of embodiment towards the personalized avatar and body awareness before and after the body swap, reflecting a pre-post swap effect. The participants were divided into two conditions, with some swapping into a visible swap avatar (re-embody) while others swapped into a position without embodying a swap avatar (de-embody). Dependent variables included the sense of embodiment towards the personalized avatar, body awareness, and self-compassion. Additionally, the sense of embodiment towards the swap avatar was evaluated once after the body swap. Finally, participants answered qualitative interview questions on UX and body awareness after the VR experience.

Main Result While bottom-up processes of sense of virtual embodiment partly passed over to the new avatar, the top-down self-identification remained with the personalized avatar even after the body swap (RQ 1, RQ 3). However, this effect on sense of embodiment towards the personalized avatar did not depend on the swap avatar's visibility (RQ 2). While self-compassion remained unaffected, participants' body awareness was increased after the body swap (RQ 4) but was not affected by swap avatar visibility (RQ 5). Further, the sense of embodiment towards the personalized avatar (after the swap) was positively related to the participants' body awareness (RQ 6). Based on these results and the qualitative answers of the participants, I derived a set of affordances for future research and design in the context of body swap-based virtual mind-body interventions (RQ 7).

Contribution The contribution of this chapter is twofold. On the one hand, it presents a distributed body swap system that allows users to switch perspectives in real-time. On the other hand, it contributes new insights into the simultaneous sense of embodiment towards personalized and non-personalized avatars during a body swap scenario and puts them in the context of body awareness. Virtual body swap experiences can be an innovative milestone for all interventions that work with perspective change. Therefore, this chapter contributes groundbreaking results for such systems' effects and future design.

Chapter 7: Effects of Body Language Similarity

Title Exploring Agent-User Personality Similarity and Dissimilarity for Virtual Reality Psychotherapy

Topic This chapter investigates how body language of a personalized virtual body affects the perception of its personality and self-identification in preparation to evaluating its effects on body awareness. In doing so, this study is a next step, after Chapter 6, in elaborating the effects of a position discrepancy between a user and a personalized, photorealistic virtual body. While in this pilot study we did not assess the participants' body awareness, this study points towards future work in encompassing the effects of virtual position- and body language discrepancies on the user's avatar- and self-processing. The study in this chapter investigated the following research questions:

RQ 1: Does the body language of a personalized agent in VR affect the perception of its personality?

RQ 2: Does the appearance personalization of an agent in VR affect the perception of its personality?

RQ 3: Do personality similarity and appearance personalization affect self-identification with an agent in VR?

Method Eleven subjects observed and rated four personalized agents and four generic agents, each selectively animated to simulate a specific personality trait: high extraversion, low extraversion (introversion), high emotional stability, and low emotional stability (emotional instability).

Main Result The findings show that while body language affected personality ratings in personalized and generic agents (RQ 1), the agent's appearance did not significantly affect personality ratings (RQ 2). Regarding the effects on self-identification (RQ 3), the study revealed a positve relationship between personality congruence and self-identification with an agent, independently of its appearance. Interestingly, participants rated the appearance-similarity of a non-personalized agent higher with higher personality congruence, while the personality congruence did not affect the appearance-similarity ratings of personalized agents.

Contribution This chapter presents a system that allows personalizing virtual humans not only in terms of their appearance but also in terms of their body language for the design of future mind-body intervention settings. It shows how much a personality trait is recognized in personalized and non-personalized agents. Finally, it indicates to what extent the perception of personalized agents is affected by body language and how this evaluation depends on a personality congruence between user and agent. This research points towards future work in designing VR mind-body interactions that include virtual self-encounters. The next step will be to test whether the body language of personalized agents perceived from a third-person perspective affects not only self-identification but also other embodied and/or conceptual self-related and avatar-related processes.

Findings

In the studies in this thesis, I gathered some insights into the perception of virtual bodies, delving into the intricate relationship between virtual bodies, the corporeal body and the soma in VR mind-body interventions. The results of my experiments reveal exciting new insights with a focus on how virtual bodies as immersive features (Wienrich et al., 2021) affect the sense of virtual embodiment and body awareness[7] as possible moderators of therapeutic success. In the following, I discuss how these insights contribute to answering my research questions.

The Relationship of Sense of Virtual Embodiment and Body Awareness

My first research question was: *Which dimensions of the sense of virtual embodiment are related to body awareness?* Over the course of my empiric work, all three dimensions of the VEQ, virtual body ownership, agency, and change in body schema, revealed some relationship to body awareness ratings. The key findings were as follows:

- ➔ A high feeling of sense of virtual body ownership mostly indicates high body awareness.
- ➔ A high feeling of agency over a virtual body indicates high body awareness.
- ➔ The relationship between experiencing a change in body schema and body awareness depends on the setting.

These findings support the use of self-avatars in VR therapy, as long as high ownership and agency over the avatar are guaranteed. They further suggest caution in designing change experiences and open up the question of whether we can introduce change in body schema without harming body awareness. In the following, I discuss the findings for each dimension of the VEQ in detail.

Body Ownership I found a positive relationship between corporeal body ownership and body awareness (Chapter 4). Regarding virtual body ownership, I also, repeatedly, found a positive relationship (Chapters 3, 4, 5, and 6), mostly calculated for post-VR measures. These findings indicate that experiencing (virtual) body ownership and body awareness go hand in hand. I discuss possible reasons for this in the various chapters. One of them is that low virtual body ownership may indicate a rather separate perception between the virtual and the corporeal body. This could indicate that the processing of signals from the virtual and corporeal bodies compete with each other, leaving less capacity for the soma and, thus, for body awareness (Mejia-Puig & Chandrasekera, 2022). In this case, the virtual body might not be integrated into the self-processing but is rather processed separately. Conversely, higher virtual body ownership could indicate that the virtual and corporeal bodies are perceived in an integrated manner or that the perception of the virtual body overshadows the corporeal body, which would allow more space and capacity for body awareness and processing of the soma. In view of the findings regarding virtual body ownership and body awareness, it might, therefore, be concluded that integrated processing is a prerequisite for a virtual body to promote a positive rather than a negative effect on body awareness.

[7]Please note that I refer to body awareness as a whole in this section. For a more detailed breakdown of the dimensions of body awareness, I refer you to the individual chapters of this thesis.

Chapter 5, revealed a surprising effect that shows that a design with a high sense of virtual body ownership does not necessarily result in the highest body awareness. While participants with a personalized virtual body reported the highest sense of virtual body ownership, they reported the lowest body awareness. From this result, I conclude that although the sense of virtual body ownership is an important measure for predicting body awareness, it should not be the only measure, as other possible UX factors could also have an influence, such as possible distracting effects due to personalization.

Agency Next to that, I found a positive relationship between perceived agency over a (personalized) virtual body and body awareness (Chapters 3, 4, 5, 6). I found that agency mediated the effect between virtuality and body awareness (Chapter 4). These results match the results on virtual body ownership and add a bottom-up component. Again, they indicate that congruence between a virtual body and the corporeal body (which is a strong indicator for agency (Mottelson et al., 2023)) might be fundamental for maintaining body awareness in avatar embodiment. A possible explanation might, again, lie in the mental capacity for processing the soma. High agency is an indicator for low bottom-up perceptible discrepancy between the avatar and corporeal bodies' movements. Thus, in scenarios with high agency, users do not have to integrate potential mismatches between their corporeal movements and the movements they are confronted with visually.

Regarding the qualitative results from Chapter 2, it is conceivable that creating small deviations in avatar movements might have the potential to affect body awareness - both positively and negatively. In addition, the results in Chapter 6 indicate that a reduction of agency due to a body swap does not necessarily lead to a reduced body awareness. However, the results for avatars perceived from a first-person perspective still indicate the necessity of aiming for high agency to ensure body awareness.

Change in Body Schema Finally, the relationship between perceived change in body schema and body awareness varied between studies. In Chapters 3 and 5, I did not find a relationship. However, the results of Chapter 4 indicate a negative relationship between change in body schema and body awareness. Here, change in body schema mediated body awareness, indicating that a higher change in body schema leads to more focus on the *outside* and less focus on the *inside* of the body. Contradicting these results, in Chapter 6 I found a positive relationship between feeling a change in body schema and body awareness.

The reasons for these mixed results may lie either in the nature of change in body schema as a dimension of sense of virtual embodiment or in the mixed character of my studies. Change in body schema is the dimension of the VEQ, which differs from the definition of sense of virtual embodiment by Kilteni, Groten, et al. (2012). Roth and Latoschik (2020) define it less as a part of perceiving the virtual body but as a means to measure how the virtual body affects the perception of the corporeal body. It is, thus, closer to the idea of an integration of avatar- and corporeal processing beyond controllability or appearance. Thus, a change in body schema may behave differently than a sense of virtual body ownership or agency.

Since I worked with various variations of discrepancy between the corporeal and virtual bodies, a perceived change in body schema might have been interpreted differently by participants of different studies. In Chapter 4, a feeling of change in body schema could have been perceived as more negative due to the direct comparison to just perceiving the corporeal body. On the other hand, the positive effect in Chapter 6 could be due to the fact that the perspective change brought about by the body swap is recognized and emphasized as an intervention goal. However, deeper work is needed here to determine to what extent change in body schema reacts to such nuances and whether a valence measure of the change being perceived as positive or negative could be an additional helpful evaluation option.

Replacing the Body: Virtual vs. Corporeal Embodiment

The second research question in this work was: *Compared to only corporeal body embodiment, does avatar embodiment affect body awareness?* This question was mainly answered in Chapter 4, where we found an effect of avatar embodiment on body awareness in a scenario with photorealistic personalized virtual bodies in a virtual environment designed to be as close to reality as possible, but also in some of the other chapters where participants expressed their experiences during avatar embodiment. The key findings regarding the second research question are:

- ➔ Embodying virtual bodies reduces body awareness - compared to solely embodying one's corporeal body.
- ➔ Embodying virtual bodies is accompanied by reduced feelings of body ownership and agency and increased feelings of change in body schema, partly explaining the effects on body awareness.
- ➔ A mirror image is not essential for maintaining a sense of virtual embodiment and may even distract from non-visual body signals.
- ➔ There is individual variability in the effects of avatar embodiment on body awareness.

The first two findings show that even the most realistic depiction of reality represents an initial discrepancy between the virtual and corporeal body, which has an impact on body awareness. In addition to body awareness, such feelings of ownership and agency were lower in avatar embodiment than in reality and the feeling of change was higher in body schema. Taking into account the correlations between the measures of sense of virtual embodiment and body awareness, it can be concluded that avatar embodiment may result in altered self-processing, which may be explained by the altered processing of the virtual body compared to the corporeal body.

However, participants responded very individually in their qualitative statements on their body experience during avatar embodiment. While some felt distracted from their soma, others experienced attention being drawn to the inside of their body through small deviations between avatar and corporeal body. This indicates that tuning to individual needs is necessary.

These findings suggest that a virtual self-representation is perceived differently from the corporeal self. They further suggest that a virtual self-representation can negatively affect somatic self-processing. They further indicate that caution is required when using VR in mind-body interventions to cater toward body awareness. In the following, I discuss the findings for both the sense of virtual embodiment and body awareness in detail.

Sense of Embodiment In Chapter 4, I revealed that the corporeal body, while not producing a ceiling effect, led to a higher sense of body ownership and agency than a virtual body. Accordingly, participants felt more change in body schema when confronted with a personalized virtual body rather than their corporeal body. While we presented the participants with an additional mirror perspective on their corporeal or virtual bodies, the presence of this mirror image did not enhance that effect.

It seems reasonable that the sense of embodiment is higher towards the corporeal body than towards an avatar. It would be an exciting next step to investigate how the embodiment of a virtual body affects the sense of embodiment toward the corporeal body and whether that might be a risk factor for depersonalization or dis-embodiment in certain groups of participants (Barreda-Ángeles & Hartmann, 2023).

The scores of the sense of embodiment toward the corporeal body not being maxed out might give some food for thought. However, the experimental situation and being questioned about the sense of embodiment toward the corporeal body might have led to a similar situation as in the experiment of Usoh et al. (2000), who found out that participants did not score their presence at maximum even when being in a physical environment instead of a virtual one. These findings may provide a new basis for interpreting the height of the sense of body ownership and agency ratings towards virtual bodies.

The fact that a mirror does not affect the sense of embodiment compared to the virtual body goes hand in hand with other studies on the effect of mirrors on the sense of embodiment (Inoue & Kitazaki, 2021; Rey et al., 2022). Regarding the corporeal body, one reason could be that individuals are familiar with their mirror image and therefore did not experience novelty during the experimental process.

Body Awareness Regarding body awareness, in Chapter 2, I qualitatively assessed whether participants felt aware of their corporeal body and soma during a virtual experience that included a photorealistic, personalized self-avatar, which they modulated over time regarding their body weight. Some participants reported that they felt in contact with their corporeal body. They stated that movement tasks during the VR experience helped them be aware of their corporeal body, especially highlighting a gesture-based interaction proposed in the experiment. However, other participants stated a loss of contact with their soma. They reported a prioritized focus on the task and the avatar instead of their body and a distraction by the virtual surroundings. Finally, some participants reported feeling bodily changes while embodying their avatar. One reported an attention shift toward their corporeal body due to mismatches in body posture between themselves and the avatar. Another participant reported feeling heavier and lighter with the changing avatar body weight. Overall, the reports on body awareness were highly individual among participants.

In Chapter 4, I tested whether photorealistic, personalized virtual bodies affected participants' body awareness compared to their corporeal bodies. I found a significantly lower rating in the self-reported body awareness in VR compared to the corporeal environment, combined with an increased focus on visual rather than non-visual signals. Having an additional mirror perspective on the respective body, participants reported focusing more on visual signals when a mirror was shown, irrespective of whether they saw their virtual or corporeal body. However, I did not find an effect of a mirror perspective on body awareness ratings. All effects found in Chapter 4 relate to in-experience measurements. A measurement after the experience did not reveal differences between the corporeal and virtual body.

Comparing VR to reality, simply embodying a virtual body already has consequences for the user's body awareness. They feel like they notice fewer body signals, find it harder to regulate their attention to the body, and are more absorbed with visual signals - while at the same time identifying less with the "new", virtual body than with their corporeal body. This should be taken into account when designing for VR mind-body interventions. However, the results from Chapter 2 suggest that, at least for certain target groups, the use of avatars can be an opportunity to strengthen or purposefully integrate body awareness.

Creating Discrepancies: The Impact of Incongruence

The third research question in this thesis was: *How do factors that increase the discrepancy between the virtual body and the corporeal body affect the sense of virtual embodiment and body awareness?* Here, I found different effects with regard to the different variations of discrepancy. The key findings regarding this research question are:

- ➔ Embodying a personalized avatar increases sense of virtual body ownership compared to non-personalized avatars but might be a distraction from the soma.
- ➔ Transitions from a first-person perspective are feasible and do not necessarily diminish identification with a personalized virtual body.
- ➔ Transitions from a first-person perspective do not necessarily create distance to one's body awareness.
- ➔ The perception of a personalized virtual body from a third-person perspective is affected by its body language but not necessarily by whether users perceive another virtual body from a first-person perspective.

The studies in this thesis increase the discrepancy between the virtual and corporeal bodies in various ways, revealing effects on both the sense of virtual embodiment and body awareness. For example, not all factors that increased the sense of virtual embodiment necessarily positively affected body awareness (see Chapter 5). Conversely, there were factors such as body swapping that positively affected body awareness but had mixed results on avatar processing. The findings regarding the different types of discrepancies show that despite a positive relationship, not every factor that strengthens or weakens the sense of virtual embodiment (and especially the sense of virtual body ownership) necessarily has the same effect on body awareness. They further indicate that introducing discrepancies between the virtual body and the corporeal body can invite the potential for strengthening body awareness. In the following, I discuss the findings for each factor of discrepancy between the corporeal and the virtual body in detail.

De-Personalization: Discrepancy in Appearance Chapters 5 and 6 compare personalized photo-realistic avatars with less customized virtual bodies. In Chapter 5, I compared personalized photo-realistic self-avatars with generic and individualized self-avatars with similar realism. I found that personalization significantly affected the sense of virtual body ownership - participants reported the highest sense of virtual body ownership levels for those conditions, even beyond the VR session. The feeling of agency showed a trend in differentiating between generic and customized avatars, but it was not significant. Regarding the change in body schema, the different types of virtual bodies did not have a significant effect. Thus, the avatar appearance might not have altered the perception of one's corporeal body or soma at this low level of dissimilarity.

In Chapter 6, I compared the sense of embodiment toward a generic self-avatar perceived from a third-person perspective with the sense of embodiment toward a personalized photorealistic virtual body controlled by another person and perceived from a first-person perspective. Participants reported a higher sense of agency over the generic self-avatar. However, I found a lower sense of virtual body ownership, self-similarity, and self-attribution toward the generic self-avatar than toward the personalized virtual body controlled by another person. I found no effect on a feeling of change in body schema or self-location, which may be due to a small sample size or may indicate a dual embodiment effect of feeling located both in the generic and the personalized virtual body.

Regarding the effects of discrepancies in appearance on body awareness, Chapters 5 and 6 reveal that avatar personalization might have a negative effect on body awareness. In Chapter 5, while heartbeat counting performance was not affected by avatar appearance, body awareness ratings were lower for personalized avatars than for customized or generic ones both in VR and post VR. In Chapter 6, participants rated their body awareness higher when controlling a non-personalized avatar from a first-person perspective than when controlling their personalized avatar. While the latter effects might be due to longer exposure time to VR, both findings indicate that being embodied in a personalized avatar might reduce the capacity for body awareness and for somatic experience.

De-Embodiment: Discrepancy in Visibility In Chapter 6, I examined the effect of an invisible virtual body in comparison to a generic self-avatar and in comparison to a personalized virtual body controlled by another person. Participants reported a reduced sense of agency when their virtual self-avatar was not visible. The other measures initially showed no significant difference, although the small number of participants must be pointed out here, which may have reduced the power of the study. There were clear differences between the personalized virtual body and the invisible body. Participants reported a lower sense of virtual body ownership, self-similarity, and self-attribution toward their invisible body than the personalized virtual body. Here, I did not find a difference in agency, change in body schema, or self-location, which, again, could be either due to a negligible effect or to the small sample size.

With regard to body awareness, Chapter 6 revealed no significant effect of having a generic visible vs. an invisible virtual body while seeing one's personalized photorealistic virtual body being controlled by another person.

De-Positioning: Discrepancy in Perspective In Chapter 6 and Chapter 7, I tackle the question of how users perceive their personalized photorealistic virtual body from an outside perspective. In Chapter 6, I compared the perception of being outside the personalized photorealistic virtual body to being inside of it. In line with expectations, I found that a body swap negatively impacted the sense of embodiment towards this virtual body. Participants reported significantly lower agency and self-similarity. However, other dimensions of the sense of virtual embodiment did not differ significantly after the swap. As mentioned above, regarding body awareness, the results of Chapter 6 revealed that the body swap did not reduce body awareness, independent of whether a participant swapped into a visible or generic virtual body.

De-Personalization: Discrepancy in Body Language In Chapter 7, I further the insights of Chapter 6 and explored whether participants identified stronger with personalized, photorealistic agents than with generic agents and whether the display of different personality-enhanced animations would affect the perception of the agents. I found a significant correlation between personality similarity, self-attribution, and perceived behavior similarity. On a descriptive note, I found that, for generic agents, personality similarity correlates with appearance similarity. However, as this work is still in progress, the question of how this body language similarity affects body awareness is a topic for future work.

Theoretical Considerations

In this section, I discuss the findings in the context of psychological embodiment research and the definition of embodied self- and avatar-related processing. Situating the findings within this larger framework deepens the understanding of the implications and potential pathways for further VR mind-body interventions.

Bottom-Up and Top-Down?

As introduced above, top-down and bottom-up processes decisively influence the self-related processes in mind-body interventions and the processing of virtual bodies during avatar embodiment. The classification of interoception as an embodied self-related process (Britton et al., 2021) and the definition of body awareness as the conscious realization of internal body signals (Mehling et al., 2009) could lead to the conclusion that body awareness is only influenced bottom-up by internal processes. However, the findings in Chapter 5 show that during avatar embodiment, top-down processed information such as the appearance of the avatar does affect measures of body awareness. This result is in line with previous work that showed top-down effects of external stimulation such as mirror exposure (Ainley et al., 2012). The empirical work in Chapters 4 to 6 contributes to the understanding of how top-down or bottom-up processes during avatar embodiment impact the sense of virtual embodiment and body awareness.

Chapter 4 investigated how replacing all visual information about the environment and the body with virtual embodiment affects body awareness. This switch from a corporeal to a virtual environment and body has both top-down and bottom-up oriented elements. To date, the appearance of personalized, photorealistic avatars still is not a perfect copy of the corporeal body, which was also pointed out by some participants in the qualitative interviews in Chapter 2 and 6. This could explain the effects of VR on body ownership, which, as an intermediate avatar-related process (s. Figure 3), is more susceptible to top-down incongruences between appearance and user expectations (Mottelson et al., 2023). On the other hand, to date, motion tracking and real-time avatar animation still include some latency and some deviations between user and avatar movements. These might explain the effects on agency ratings, which are more prone to the bottom-up influence of visuomotor incongruence (Mottelson et al., 2023). The study in Chapter 4 revealed a mediating effect of agency and of change in body schema for the effect of VR on body awareness but not of the sense of virtual body ownership. This suggests that for body awareness in avatar embodiment, bottom-up processing may play a larger role than top-down processing. This is consistent with the results from previous studies that found the effects of different bottom-up stimulation on interoception (Filippetti & Tsakiris, 2017).

Chapter 5 investigated the effects of avatar appearance on body awareness. In doing so, it revealed that the avatar's appearance and, thus, the congruence between the user's corporeal and virtual body can affect body awareness top-down. However, the results opposed the initial expectations, indicating some independence between body awareness and top-down affected sense of body ownership. This result might be explained by mental load theories (Mejia-Puig & Chandrasekera, 2022) or reinforce the idea of visual dominance over other signals in the existence of interesting visual information (Stokes & Biggs, 2014). Moreover, it reveals a top-down effect of avatar embodiment on body awareness, which cannot solely be explained by the sense of embodiment towards the avatar.

In Chapter 6, leaving the first-person perspective of one's personalized avatar reduced the sense of virtual embodiment, particularly affecting more bottom-up oriented dimensions. Despite bottom-up effects on the embodied avatar-related processes, strong self-attribution and sense of body ownership did not alter significantly. Participants continued to identify with and experience a sense of body ownership over their personalized avatar. This result highlights the distinction between bottom-up processed avatar position and control and top-down identification with it. As with regard to body awareness, the increase of body awareness after the swap might contradict the findings in Chapter 4 that indicated a stronger bottom-up than top-down relationship between sense of virtual embodiment and body awareness. Still, I found positive relationships between sense of virtual embodiment and body awareness. The effects of the different conditions on body awareness again showed some independence from effects on sense of body ownerhsip, agency, or change in body schema. These findings indicate that a position discrepancy and respective bottom-up effects on sense of virtual embodiment do not necessarily affect body awareness. However, identifying whether the increase in body awareness that is due to these position changes or can be explained by other top-down or bottom-up oriented factors remains open for future work.

In conclusion, the study findings reveal several key insights regarding the relationship between sense of virtual embodiment and body awareness in the presence of varying top-down and bottom-up information:

- ➔ There exists a relationship between both top-down and bottom-up influenced dimensions of sense of virtual embodiment and body awareness.
- ➔ In situations with a high level of congruence between reality and VR, dimensions of sense of virtual embodiment primarily influenced by bottom-up processes tend to have a more pronounced effect on body awareness.
- ➔ The similarity between an avatar and the physical body exerts a top-down influence on body awareness, distinct from the impact of avatar appearance on the sense of body ownership. This suggests differences in the acceptance of the avatar from a top-down perspective and the degree to which one can focus on internal body signals when exposed to new visual information. Additionally, these findings indicate that body awareness remains resilient against significant visual discrepancies between the self and the avatar.
- ➔ Concerning changes in perspective, the bottom-up effect on the sense of virtual embodiment appears to be stronger than on body awareness. Furthermore, body awareness demonstrates independence from the sense of virtual embodiment when experiencing one or multiple virtual bodies from a first-person perspective. This suggests the ability to maintain body awareness even as bottom-up information about body position or top-down information about the appearance of a first-person avatar changes.

Replacing the Body in Embodiment

This thesis investigated several scenarios where participants interacted with virtual bodies that differed from their corporeal bodies in terms of appearance, perspective, or body language. These virtual bodies were either controlled by the participants themselves, by other people, or purely computer-animated. In the context of the previously introduced definition of embodiment and avatar embodiment, it, thus, revealed some insights into how users perceive their *self* in the presence of such virtual bodies. In the following, I discuss whether a virtual body can be seen as an extension, manipulation, or even replacement of the corporeal body and whether avatar-processing can be defined as a tool to refine self-related processing in future VR mind-body interventions.

Having More Than One Body

As mentioned above, an individual's self preception can be seen as a continuum between the *pre-reflective self* and the *reflective self* (Britton et al., 2021; Wehrle, 2020), including embodied and conceptual self-related processes. Further, the embodied self-related processing includes the duality of the corporeal body as an object and the soma as a perceptual medium (Shusterman, 2012). In VR, this relationship changes as users no longer receive any visual information about the corporeal body. In the case of avatar embodiment, the visual information is replaced by a virtual body. The findings of my studies support the assumption that this replacement of the visual body signals affects the embodied and intermediate processing of the virtual body and the soma, namely, on body awareness. Chapter 4 follows the assumption that a virtual body can be a full substitute for the corporeal body as long as the virtual body is as similar as possible to the corporeal body and can be controlled by the user from a first-person perspective. However, the study revealed significant effects on all measured dimensions of the sense of virtual embodiment and on body awareness, indicating differences between self- and avatar-related processing.

But how can we define a *replacement of the corporeal body* in VR? To determine whether the findings of this thesis indicate that avatars might replace or substitute the corporeal body and to determine whether such a replacement is desirable for VR mind-body interventions, it is necessary to first define what effect a replacement would have.

First, reaching a replacement might mean reaching the highest possible ratings on scales for embodied, intermediate, or conceptual avatar-related processes. In line with prior work (Mottelson et al., 2023), in my studies, this was the case in situations where there is a strong appearance similarity between the user and the avatar and when the user controls it from a first-person perspective. Under these circumstances, the findings suggest that replacement might be a goal that should be avoided for the use in mind-body interventions. While these situations achieved high ratings on the sense of virtual embodiment, body awareness ratings were reduced compared to other situations. In view of this, the therapeutic application should rather not aim at the replacement of the corporeal body, as it might possibly be seen as a factor that distracts from the awareness of the body.

A second definition of a replacement would be that a user is fully absorbed with their virtual body and that the coporeal body recedes into the background of their perception. It, thus, would mean a full integration of embodied self- and avatar-related processing. Examples for this might be studies demonstrating the effects of avatar embodiment on the perception of body dimensions (Kilteni, Groten, et al., 2012), movements (Kasahara et al., 2017), or positions (Guterstam et al., 2020). As a result, the two bodies would no longer be perceived as competing with each other and thus would not create additional mental workload in processing their discrepancies (Mejia-Puig & Chandrasekera, 2022). In terms of body awareness, this would mean that there would be just as much capacity for body awareness in VR as outside VR. Striving for a replacement would, thus, be advantageous for VR mind-body interventions. In line with prior work (Fribourg et al., 2020), with this definition in mind, the results on body awareness suggest that personalization and realism might not necessarily be the highest goal in finding a replacement of the corporeal body (Chapter 5). Rather, exploring how an integration between the virtual and corporeal body impacts the processing of the corporeal body, namely the sense of body ownership and agency towards it, might be of use in further exploring whether a virtual body can replace the processing of the corporeal body.

It is the contradiction between body awareness and the sense of virtual embodiment that shows that maintaining body awareness requires different approaches than solely focusing on increasing the sense of virtual embodiment. Regarding the two potential meanings of replacing the corporeal body, the second approach might be more adequate for VR mind-body interventions. Based on the results, this thesis indicates that the use of non-personalized avatars or stereotypical, task-specific avatars as in scenarios aiming for a Proteus effect(Mal et al., 2023; Praetorius & Görlich, 2020; Yee & Bailenson, 2007) not necessarily is a threat to the preservation of body awareness. Indeed, the effects indicate that the embodiment of non-personalized virtual bodies enables higher body awareness than personalized virtual bodies. In conclusion, the study findings reveal several key insights regarding the question of whether avatars can and should replace the corporeal body in VR mind-body interventions:

➔ With the current technical possibilities, a full replacement of the corporeal by the virtual body is not yet possible.

➔ Replacement can mean striving for the highest possible level of body ownership and/or agency, in which the virtual body is perceived as "one's own". Since body awareness is not affected by the same factors as body ownership or agency, striving for replacement in that meaning seems rather unsuitable for use in mind-body therapy.

➔ Replacement can also mean a successful integration of avatar and self-related processing, in which the corporeal body recedes into the background. In this case, the results indicate that body awareness might not be affected negatively by replacement. Replacement would, thus, be a conceivable goal for use in therapy.

Leaving The Body Behind

In the last two chapters of this thesis, I addressed the topic of leaving the (virtual) body behind, of taking new perspectives on one's personalized avatar, and the effects that might come with such spatial distancing. Again, I have considered two conditions: the user within their personalized virtual body and outside their personalized virtual body. Furthermore, I have shown the possibility of personalizing the behavior of the virtual body for the area of a virtual external perspective. While there are a number of further differentiation, my findings already allow for an initial interpretation of the effects of leaving the body behind.

There is some preliminary work on personalized avatars in which users view video recordings of their corporeal body (Cebolla et al., 2016; Landau, 2020) or their personalized virtual body, or variants thereof (Mölbert et al., 2018; Wolf et al., 2021) from an outside perspective without being able to control it. Cebolla et al. (2016) did not find an effect of their version of a virtual out-of-body experience on body awareness compared to a guided meditation. However, they found a positive pre-post effect. Similarly to that, I found a positive effect of a virtual body swap on body awareness (see Chapter 6). With regard to a sense of virtual embodiment, former work has shown that users can experience some sense of body ownership over virtual bodies that are located in a different position than themselves, and even, if they are not able to control them (Mottelson et al., 2023). These results are countered by other studies that postulate a so-called disembodiment effect, which describes a detachment from an avatar due to sensory mismatch or position (Mottelson et al., 2023).

Chapter 6 revealed that participants continued to experience a high sense of virtual body ownership even when they left their personalized virtual body behind. Further, it showed that the sense of embodiment towards said personalized virtual body perceived from an outside perspective, at least bottom-up, is comparable to the sense of embodiment towards a generic virtual body perceived from first-person perspective at the same time. The question now arises as to whether spatially leaving the personalized virtual body behind has a disembodiment effect not only on the embodied, but also on a conceptual level of avatar-related processing. With regard to the usage in mind-body interventions, creating such a disembodiment or disassociation with the virtual body might be a useful tool to create a situation of therapeutic self-distancing (Kross & Ayduk, 2017). Chapter 7 is a first step towards further increasing discrepancy between the user and their personalized virtual body on a conceptual level. It showed that participants feel less top-down association with a personalized agent depending on their body language. In order to create distance, but also to stimulate self-related processing on several levels, the behavior of avatars could, thus, be a helpful tool in VR mind-body interventions in addition to perspective.

However, the results in these two chapters raise the question of what happens to the perception of the corporeal body and soma when we are confronted with more than one virtual body at the same time. Related work on dual- or multi-embodiment (Guterstam et al., 2020) indicates that there is a mental capacity to experience ownership over more than one body. In this work, the dual embodiment can be separated into a conceptual ownership based on personalized appearance and a bottom-up sense of virtual embodiment based on perspective and controllability. An overlap or intersection of these variants of avatar embodiment is conceivable, for example, through the personalization or variation of virtual agents with regard to the user's body language. In future work, these should be investigated with regard to their relevance for the body perception and self-concept of users.

In summary, the findings in this thesis allow for some conclusions regarding the effects and potentials of leaving a personalized virtual body behind:

- ➔ Leaving a personalized virtual body behind results in a reduced sense of embodiment towards it.
- ➔ However, while users reported some changes in perceived self-similarity, leaving a personalized virtual body behind does not necessarily affect the sense of virtual body ownership and, on a conceptual level, self-attribution.
- ➔ Self-reflection requires self-distancing. The reduction of ratings of sense of virtual embodiment during a body swap while maintaining body awareness shows potential for the application of virtual out-of-body scenarios as a tool for mind-body interventions. The reduction of conceptual avatar-related processes with increased body language discrepancy further supports this potential.

Limitations and Future Lines of Research

While this thesis's findings provide insights into the relationship between avatar embodiment, avatar-related processing, and body awareness, they do not comprehensively explain the full complexity of virtual and corporeal bodies and of self- and avatar-related processing. However, they pave the way and set outlines for future work toward the integration of body awareness in virtual mind-body interventions. In this section, I acknowledge some limitations of the current work and discuss the potential for future research and design that might be derived from my findings.

Amplifying Virtual Self-Encounters

The selection of avatars in my studies covers only a small range of possibilities of avatar embodiment regarding avatar appearance, the interplay of avatars and virtual environment, and with regard to virtual self-encoutnters. First, my studies focus on anthropomorphized avatars and, in particular, on the representation of and interaction with photorealistic, personalized avatars. This is in contrast to the broad spectrum of dissimilar avatar design (Cheymol et al., 2023) and also the desire of participants to embody other, non-human avatars (s. Chapter 6). Exploring how embodying non-human avatars influences body awareness falls beyond the scope of this work. However, variations of a user's virtual body outside the spectrum of realism and personalization hold great potential for VR intervention settings. Osimo et al. (2015) have shown that embodying a virtual therapist can positively affect self-counseling results. Similarly, Falconer et al. (2016) showed that embodying a virtual child might help increase self-compassion. As shown in Chapter 5, the use of non-personalized anthropomorphic virtual bodies certainly has the potential not only to not reduce, but increase body awareness compared to photorealistic personalization. Regarding mind-body interventions, investigating further possibilities of avatar design and possible effects on body awareness and other self-related processes could, thus, expand my results vividly. Future work could build on my findings on avatar personalization and, similar to the maximum-similarity example from Chapter 4, create a minimum scenario that represents the minimum requirements for a system in which body awareness is still at a tolerable level.

In addition to avatar appearance, examining variations in virtual environments might be the next step in exploring the effects of avatar embodiment on body awareness and in the design of VR mind-body interventions. As shown in Chapter 1, current mind-body interventions often use nature-inspired environments to create feelings of awe or calmness. In contrast, my studies focus on indoor environments, either imitating a laboratory room or a psychotherapist's office. The VR environment has the potential to affect avatar-related processing (Mal et al., 2023) and, thus, might affect the user's capacity for self-related processing. Investigating how virtual bodies in interplay with varying virtual environments affect body awareness could, thus, be crucial for the design of avatar-based VR mind-body interventions.

Moreover, the perspective on the virtual body of a user is limited in my studies. While Chapters 6 and 7 presents two possibilities on how a user could encounter their virtual representation from an outside perspective, several variations of such virtual self-encounters are imaginable. In Chapter 6, I discuss a variety of future designs and developments of such self-encounters that could amplify the findings of these studies in creating therapeutical applications. The next step in my future work will be to expand the findings of Chapter 7, by investigating the effects of the behavior of personalized agents on self-perception and body awareness.

Finally, the type of interaction in VR and the duration of the interaction in my studies were also limited. Participants were in the virtual environment only once, for a comparatively short period of 15 to 30 minutes, performing either a set of movement tasks or an additional guided meditation. This limitation is in contrast to the diverse interaction possibilities that VR allows us with regard to the virtual environment, virtual objects, virtual others, or the virtual self-representation (Wienrich, Döllinger, et al., 2018). Additionally, it is in contrast to the typical design of mind-body interventions that are usually practiced over the course of several weeks to ensure long-term effects (Gyllensten et al., 2018). Therefore, future work should explore to what extent other, more VR-specific forms of interaction, and especially how repeated confrontation with an avatar affect body awareness and whether the effects found in this work change with repetition.

Applying Novel Measures of Body Awareness and Sense of Virtual Embodiment

Next to limitations in the variety of avatar embodiment scenarios, the dependent variables investigated in this thesis also need to be revisited. Concerning body awareness, this work was limited primarily to quantitative self-report measures of body awareness and used an additional heartbeat counting task mainly as a control measure. During and shortly after data collection, three interesting novel measures of body awareness or interoceptive accuracy in VR were published. A qualitative measure to capture users' subjective body awareness by Haley et al. (2023), a quantitative questionnaire to capture embodied mindfulness by Khoury et al. (2023), and a quantitative performance measure based on in-VR heart recognition as an alternative to heartbeat counting (El Ali et al., 2023). While heartbeat counting has long been the standard measure for detecting interoception (Desmedt et al., 2022), its validity in assessing interoception independently of time estimations has been discussed critically (Ainley et al., 2020; Corneille et al., 2020; Zamariola et al., 2018; Zimprich et al., 2020). Recognizing the correctness of displayed heartbeats has the potential to make the detection of interoceptive accuracy even more accurate as it is independent of prior knowledge and time estimations (El Ali et al., 2023). Investigating the effects of avatar embodiment and VR mind-body interventions on these measures may yield interesting new results. The use of qualitative measures, in particular, could potentially be decisive for developing design guidelines for such interventions.

With regard to avatar-related processes, my results are also limited by the choice of the VEQ as the main measure of the sense of virtual embodiment. The VEQ emphasizes the sense of virtual body ownership and agency and introduces an integrated assessment for change in body schema. Other dimensions of avatar-related processing, such as self-location or conceptual avatar-related processes, are therefore not taken into account. Here, future work should further investigate the impact of other measures of sense of virtual embodiment, be it other rating scales or behavioral and physiological assessments.

Additional Dependent Variables

My studies are limited to the relationship between a small range of avatar-related processes and body awareness. Therefore, the results can only provide little information about the extent to which avatar embodiment causes other embodied self-related processes, such as body ownership or agency over the corporeal body, to recede. Future research will bring insights into how these self- and avatar-related processes mirror each other and whether virtual bodies have the potential to overwrite embodied self-related processes outside body awareness.

Additionally, incorporating more dependent variables will be crucial to explaining the inconsistencies I found in the relationship between the sense of virtual embodiment and body awareness. As mentioned above, one possible explanation of differing effects between body awareness and sense of virtual body ownership might lie in mental capacity for self-related processing (Mejia-Puig & Chandrasekera, 2022). However, while I tested a variety of VR UX measures, none of my studies included an assessment of mental workload. Future work might deepen the understanding of the relationship between sense of virtual embodiment and body awareness by evaluating their relationship to mental workload and capacity. As a second explanation of the effect differences between a sense of virtual body ownership and body awareness, I suggested visual distraction. One measure to explain a distraction by personalization could be capturing the user's gaze behavior (Döllinger et al., 2022). There is already work that examines gaze behavior during avatar embodiment in relation to body image disorders (Porras-Garcia et al., 2020). Analyzing eye-tracking data during avatar-based mind-body interventions could help explain whether the negative effects of personalization on body awareness may be based on distraction by visually perceived details of the personalized virtual body.

Exploring Target Group Specifications

A major limiting factor in my work is the selection of samples across the studies. While I collated results from tests with over 190 participants, the subjects in the different samples were not very diverse. All studies were conducted in a laboratory at the University of Würzburg with mainly undergraduate and graduate students as study participants. The majority of the participants were white, German, under 30, with no known mental disorders, and with little to moderate previous experience with VR and mind-body exercises. Therefore, to expand the interpretation to a more diverse population and overall for an extension for use in mind-body interventions with individuals with mental disorders, further studies are essential. Only testing with the respective target groups allows for statements on whether embodying virtual avatars or virtual out-of-body experiences and multi-embodiment scenarios can be sensibly used as a therapeutic tool.

To enable the embedding of virtual bodies, be it in the form of personalized avatars or agents, in the form of mindful virtual bodies, or in any other form of therapeutically applied mind-body interventions, it is necessary to examine these scenarios with regard to possible target groups and their vulnerabilities (Han et al., 2022; Peckmann et al., 2022; Porta et al., 2024; Preston & Ehrsson, 2018). The results of this thesis show potential therapeutic use. Working with virtual bodies facilitates experiencing the body from a new distance, be it through spatial perspective, behavior or a gradual reduction of similarity between natural and virtual body. Future work should investigate the extent to which possible obstacles or risks to the use of VR and avatars could exist for different target groups. Future work might dive deeper into the possibilities of virtual self-encounters by specifying relevant target groups, their vulnerabilities, and needs and using the opportunities of VR for innovative VR based mind-body interventions.

System Specifications

Finally, the results of my studies are limited to high-end VR-systems using expensive head-mounted displays, elaborate motion capture systems, and avatar animation. To date, it is not common for psychotherapists to use such a system, let alone for users to have one in their homes. Even with an increase in households with VR devices, investigation is necessary on the extent to which the embodiment of avatars in less elaborate setups and with possibly increased visuo-motor discrepancies could have an impact on the body awareness of users. Visuomotor congruence, in particular, is a factor in the perception of a sense of virtual embodiment (Mottelson et al., 2023). Given the relationship between body awareness and agency, virtual body ownership, and change in body schema ratings, such system variations might also affect body awareness. Therefore, conclusions about such systems should only be drawn with caution and tested before use.

Conclusion

The research presented in this thesis delves into the intricate relationship between virtual bodies, sense of virtual embodiment and body awareness. I investigated which dimensions of the sense of virtual embodiment are related to body awareness (RQ 1). I examined whether avatar embodiment, compared to solely corporeal embodiment, affects body awareness (RQ 2). Finally, I assessed how factors that increase the discrepancy between the virtual and corporeal body influence the sense of virtual embodiment and body awareness (RQ 3). My findings reveal a spectrum of responses to avatars, demonstrating that processing a virtual body has the potential to both diminish and enhance body awareness. Interestingly, individual perceptions vary widely, suggesting a nuanced interplay between avatar representation and personal experience.

For RQ 1, my findings indicate that a high sense of virtual body ownership and agency over a virtual body are associated with heightened body awareness. However, the relationship between changes in body schema and body awareness is context-dependent. Regarding RQ 2, embodying virtual bodies generally reduced body awareness compared to embodying one's corporeal body. This reduction was accompanied by decreased feelings of body ownership and agency, alongside increased experiences of change in body schema, which partially explain the effects on body awareness. Notably, there is significant individual variability in how avatar embodiment affects body awareness. For RQ 3, I discovered that embodying a personalized avatar increased the sense of virtual body ownership compared to non-personalized avatars but might distract from internal bodily sensations. Transitions from a first-person perspective do not necessarily diminish identification with a personalized virtual body or create a distance from body awareness. The perception of a personalized virtual body from a third-person perspective is affected by its body language rather than by having another virtual body at hand.

On a theoretical level, my findings enrich the understanding of psychological and avatar embodiment and its implications for mental health, paving the way for future work in integrating body awareness into VR mind-body interventions. I found a dynamic interplay between top-down and bottom-up influences on both the sense of virtual embodiment and body awareness. In highly congruent VR settings, dimensions of sense of virtual embodiment primarily influenced by bottom-up processes have a more pronounced effect on body awareness. The similarity between an avatar and the physical body exerts a top-down influence on body awareness, distinct from the impact of avatar appearance on body ownership. This highlights differences in the acceptance of the avatar from a top-down perspective and the ability to focus on internal body signals despite new visual information. My findings also indicate that body awareness remains resilient against visual discrepancies between the self and the avatar.

With current technological limitations, a complete substitution of the corporeal with a virtual body remains unattainable. While striving for high levels of body ownership and agency might not be suitable for mind-body interventions, striving for an integration of avatar and self-related processing, where the corporeal body becomes less prominent, appears feasible and potentially beneficial for VR mind-body interventions. Finally, the observed reduction in the sense of virtual embodiment during a body swap, coupled with the preservation of body awareness, suggests promising prospects for utilizing virtual out-of-body scenarios as a therapeutic tool for mind-body interventions, bolstered by the attenuation of conceptual avatar-related processes with heightened body language discrepancy.

In conclusion, this thesis offers valuable insights into the complexities of avatar embodiment and its impact on body awareness. By delineating the possibilities and risks associated with avatar-mediated experiences, it lays a foundation for the development of effective and ethically sound VR mindy-body interventions.

1 Challenges and Opportunities of Immersive Technologies for Mindfulness Meditation: A Systematic Review

Döllinger, N., Wienrich, C., & Latoschik, M. E. (2021). Challenges and opportunities of immersive technologies for mindfulness meditation: A systematic review. *Frontiers in Virtual Reality, 2, 29*. doi: 10.3389/frvir.2021.644683

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This chapter was published as a journal article in Frontiers in Virtual Reality.

Author Contributions

Nina Döllinger and Carolin Wienrich contributed to the conception of the literature analysis and the manuscript and wrote sections of the manuscript. Nina Döllinger organized and performed the analysis and took the lead in writing the manuscript. Marc Erich Latoschik supervised the structuring of results. Marc Erich Latoschik and Carolin Wienrich supervised the paper writing process.

frontiers in Virtual Reality

SYSTEMATIC REVIEW
published: 27 April 2021
doi: 10.3389/frvir.2021.644683

Challenges and Opportunities of Immersive Technologies for Mindfulness Meditation: A Systematic Review

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Mindfulness is considered an important factor of an individual's subjective well-being. Consequently, Human-Computer Interaction (HCI) has investigated approaches that strengthen mindfulness, i.e., by inventing multimedia technologies to support mindfulness meditation. These approaches often use smartphones, tablets, or consumer-grade desktop systems to allow everyday usage in users' private lives or in the scope of organized therapies. Virtual, Augmented, and Mixed Reality (VR, AR, MR; in short: XR) significantly extend the design space for such approaches. XR covers a wide range of potential sensory stimulation, perceptive and cognitive manipulations, content presentation, interaction, and agency. These facilities are linked to typical XR-specific perceptions that are conceptually closely related to mindfulness research, such as (virtual) presence and (virtual) embodiment. However, a successful exploitation of XR that strengthens mindfulness requires a systematic analysis of the potential interrelation and influencing mechanisms between XR technology, its properties, factors, and phenomena and existing models and theories of the construct of mindfulness. This article reports such a systematic analysis of XR-related research from HCI and life sciences to determine the extent to which existing research frameworks on HCI and mindfulness can be applied to XR technologies, the potential of XR technologies to support mindfulness, and open research gaps. Fifty papers of ACM Digital Library and National Institutes of Health's National Library of Medicine (PubMed) with and without empirical efficacy evaluation were included in our analysis. The results reveal that at the current time, empirical research on XR-based mindfulness support mainly focuses on therapy and therapeutic outcomes. Furthermore, most of the currently investigated XR-supported mindfulness interactions are limited to vocally guided meditations within nature-inspired virtual environments. While an analysis of empirical research on those systems did not reveal differences in mindfulness compared to non-mediated mindfulness practices, various design proposals illustrate that XR has the potential to provide interactive and body-based innovations for mindfulness practice. We propose a structured approach for future work to specify and further explore the potential of XR as mindfulness-support. The resulting framework provides design guidelines for XR-based mindfulness support based on the elements and psychological mechanisms of XR interactions.

Keywords: virtual reality, augmented reality, mindfulness, XR, meditation

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Specialty section:
This article was submitted to Virtual Reality in Medicine, a section of the journal Frontiers in Virtual Reality

Received: *21 December 2020*
Accepted: *10 March 2021*
Published: *27 April 2021*

Citation:
Döllinger N, Wienrich C and Latoschik ME (2021) Challenges and Opportunities of Immersive Technologies for Mindfulness Meditation: A Systematic Review. Front. Virtual Real. 2:644683. doi: 10.3389/frvir.2021.644683

1. INTRODUCTION

"Meditation is not an escape. It is the courage to look at reality with mindfulness and concentration. Meditation is essential for our survival"—Hanh (2013), p. 121

Mindfulness and mindfulness meditation provide a counterbalance to an increasingly busy everyday life in a digitalized world, in accordance with a promise of improved mental and physical well-being. Mindfulness, "the awareness that emerges through paying attention on purpose, in the present moment, and non-judgementally to the unfolding of experience moment by moment" (Kabat-Zinn, 2003, p. 145) has, among other things, been shown to increase happiness, work satisfaction, sense of meaning, sleep quality, and symptoms of chronic pain. In addition, it provides a positive effect on cognitive abilities such as attention span, creativity or problem solving. Over the past decades, these positive effects of mindfulness have led to an increased incorporation of mindfulness practice into everyday life. A number of digital tools aiming to increase or support mindfulness have been launched to accompany this trend. Consequently, more and more research on human-computer interaction (HCI) has addressed the topic of digitally mediated mindfulness practice.

Derived from a review of HCI literature, Terzimehić et al. (2019) set up a framework for the classification of HCI research in the mindfulness context. Further, some models and frameworks exist, which define guidelines for the design of digital mindfulness support (e.g., Salehzadeh Niksirat et al., 2017; Zhu et al., 2017). While those frameworks and models mainly focus on digital mindfulness practice via smartphone apps or wearables, in recent years, researchers have addressed the question of whether Virtual (VR), Augmented (AR), or Mixed (MR) Reality (in short: XR) can positively support mindfulness practice to a greater extent. Particularly, VR provides promising characteristics that might support mindfulness and related health and well-being. For example, VR headsets offer advantages in shielding external distractors (inclusivity, Slater and Wilbur, 1997). Peripheral visual cues in XR settings further enable guiding the user's focus in a more subtle way than audio-only meditation instructions or small-screen visual guides. Further, XR provides possibilities to foster bodily or mental states (e.g., showing biofeedback). However, either embodying a virtual avatar or not having any visual body reference might distract the user from their physical body and self-focus (Khoury et al., 2017). Thus, XR experiences need to be carefully designed to ensure focus, rather than creating new distractions through overly complex designs.

In other research fields, the specific characteristics of XR have been connected to various dimensions of behavior and concrete paths of impact in XR based interventions have been analyzed (Wienrich et al., 2020). In the field of mindfulness and mindfulness related outcomes of health and well-being such analyses are lacking. Thus, the present paper systematically reviews the literature on XR-based mindfulness support to determine whether current XR systems meet the requirements for mindfulness practice and to what extent they facilitate mindfulness states. We show which aspects of mindfulness are addressed in current research and identify gaps in the research. Finally, we propose a framework combining guidelines for digital mindfulness support with XR-specific design elements and impact paths.

2. RELATED WORK

2.1. Definitions of Mindfulness

2.1.1. Mindfulness: From Eastern Philosophy to Psychological Research

Mindfulness is a multifaceted term, originated in the eastern, Buddhist philosophies, which, originated in the research of Kabat-Zinn (2003), has found increasing influence in western psychological research. The definition of mindfulness varies across disciplines and can be divided into a number of different research paths. A broad overview of possible mindfulness definitions is provided by Khoury et al. (2017), who discuss and compare Buddhist and western definitions of the term. Roughly summarized, traditional Buddhist philosophers emphasize the practitioner's focus on the here and now and place it in a context of ethical and moral guidelines (Khoury et al., 2017). Western research is based on these Buddhist ideas. Thus, the term mindfulness in western definitions is characterized by focus on current sensations and the present moment (Brown and Ryan, 2003; Kabat-Zinn, 2003; Baer et al., 2008). Regarding the operationalization of mindfulness, western research is characterized by Kabat-Zinn (2003), who dealt with the therapeutic effects of meditation and introduced a program of *mindfulness-based stress reduction* (MBSR), which has grown quite popular in psychological research. Another commonly used definition in western research is that of Walsh and Shapiro (2006). Here, the focus is not on the state of mindfulness, but rather on the connection between (eastern) mindfulness-inducing practices, e.g., meditation, and (western) psychological research. In this context, a clear difference between the two branches of mindfulness definitions becomes apparent. While Buddhist definitions tend to emphasize the intensive and daily meditative practice and growing awareness and mindfulness in daily life, western mindfulness research tends to focus on positive side effects of mindfulness, such as stress reduction (Kabat-Zinn, 2003) or other therapeutic goals (Khoury et al., 2017).

2.1.2. Mindfulness in Human-Computer Interaction

In the past decade, beyond psychological research, the field of HCI has opened up to the topic of mindfulness. For example, Derthick (2014) presented an overview of the literature on meditation practice and technology use. Also Salehzadeh Niksirat et al. (2017) and Barton et al. (2020) dealt with the influence of interactive technologies on mindfulness meditation. Similar to psychology, HCI researchers define mindfulness as a mental state of experiencing of the present moment, while the most frequently cited constructs with respect to mindfulness are increased *attention*, *presence*, experience of *body sensations*, as well as a state of *non-judgment*, *moment-to-moment awareness*, and *meditation/MBSR* (Terzimehić et al., 2019).

Additionally to the division into mindfulness as a mental state and mindfulness-inducing practices such as meditation, Brown and Ryan (2003) further suggest a division into state and trait mindfulness. This division enables to make a distinction between a general, longer-lasting predisposition to mindfulness, and a more short-term effect of individual mindfulness exercises. Terzimehić et al. (2019) presented a detailed review on HCI and mindfulness, in which they analyzed and clustered 38 articles according to their definition of mindfulness, the applied mindfulness practice, the investigated technologies used to support mindfulness, and the evaluation and recording of mindfulness. Derived from their results, they set up a framework for the classification of HCI research in the mindfulness context. This framework includes various dimensions that shape their definition of HCI mindfulness research: The *role of mindfulness* as main goal vs. mediator for other mental states, the *type of practice* such as formal meditation or informal integration of mindfulness in everyday life, the focused *co-aspects of mindfulness*, and the associated *line of research*.

In accordance with the most commonly used definitions of mindfulness in HCI, this paper addresses mindfulness as a mental state of awareness toward the current moment and sensations. On the other hand we take into account being mindful as a trait as supposed by Brown and Ryan (2003). While in HCI mindfulness research meditation often is equated with mindfulness (Terzimehić et al., 2019), we distinguish between mindfulness as a mental state or trait and meditation as a conscious practice to reach this state. Finally, we differentiate between direct outcomes of mindfulness practice, such as concentration or focus, and indirect outcomes, such as therapeutic aims.

2.2. Guidelines for Digital Mindfulness Support

2.2.1. Digital Mindfulness Support Should Provide the Feeling of *Presence-In*

Over the last couple of years a few researches have tried to build up guidelines and frameworks for the design of digital mindfulness support. Zhu et al. (2017) presented a model which addressed and clustered types of digital mindfulness support. The resulting concept includes four successive stages of digital mindfulness support: *digitized mindfulness*, *personalized mindfulness*, *quantified mindfulness*, and systems providing *presence-in and presence-with*. The first three stages they presented are all characterized by what they call *presence-through*, thus, by tools designed to provide mindfulness support. They emphasize that most of the digital mindfulness support provides a digitized form of guided meditations or mindfulness tasks, where the human teachers or meditation partners are replaced by apps or audio books (stage one). The second stage, personalized mindfulness goes beyond this simple digitization and provides *personalized mindfulness* programs, e.g., by adjusting the provided content to user preferences or demographics. The *quantified mindfulness* in the third stage feeds back the user's physiological states during mindfulness tasks in the form of adaptive performance and meditation progress. While these tools provide information about mindfulness-"performance," they are based on judging the user which contrasts the definition of mindfulness as a state of non-judgment. Zhu et al. (2017) suggest, that digital mindfulness support should be rather used to design an aesthetic background for mindful interaction, inviting to further reflect the current moment(*presence-in and presence-with*). In an analogy to nature, digital mindfulness support should invite the user to feel co-present with objects or present within a natural or digital environment that by itself provides sources for mindfulness.

2.2.2. Digital Mindfulness Support Should Include Interaction and Feedback

Similar to the criticism of Zhu et al. (2017) on digitized mindfulness, Salehzadeh Niksirat et al. (2017) highlighted that presenting auditory guided meditation is not sufficient for successful digital mindfulness support. They developed a framework for smartphone-based mindfulness interactions which follows two psychological models on mindfulness interaction, Relaxation Response (Benson and Klipper, 1975) and Attention Restoration Theory (Kaplan, 1995). Relaxation Response derives from the basic idea that mindful interactions should include slowness and repetitiveness. Attention Restoration Theory further provides guidelines for the presentation of feedback during a mindful interaction. The authors suggest that "tired cognitive patterns" should be avoided, i.e., well-known melodies or motifs. They too stress that the information presented should not evoke judgment. In addition, they suggest using simple and "soft" feedback. In summary, Salehzadeh Niksirat et al. (2017) emphasize the importance of active interactions for digital mindfulness support and provide examples for its design.

2.2.3. Digital Mindfulness Support Should Be Body Based

One important aspect that plays a central role in the work of Khoury et al. (2017) on embodied mindfulness as well as in the HCI research of mindfulness is the physical body. Besides being present in the moment, Buddhist mindfulness practice includes: body, feelings, mind, and phenomena (four establishments of mindfulness; Khoury et al., 2017). The body is essential in mindfulness practice, which in turn leads to an improved body-mind connection. So-called body-scan meditations, mindful walks, or autogenic training, which are often part of MBSR programs direct the attention toward the body. The resulting body awareness of such exercises is closely related to mindfulness (Heeter, 2016; Khoury et al., 2017). These approaches are grounded in the psychological concept of embodied cognition, which implies the interrelation of body and mind and the importance of body perceptions in cognitive processes (Wilson, 2002). Thus, as all mental states are based on body perceptions, the state of mindfulness as well must be body based. Niksirat et al. (2019) adopted the concept of embodied cognition to expand the framework of Salehzadeh Niksirat et al. (2017). The resulting framework includes the detection of body movements in order to assess the user's state of mindfulness, an assistance in self regulation via slow and continuous interactions, as suggested in Benson and Klipper (1975) and a variety of feedback to add to the state of mindfulness.

2.3. Immersive Media and Mindfulness

Over the last decade, interactions with XR technologies have attracted increasing attention in mindfulness-related research. Growing numbers of studies have been published that include XR tools or interactions that aim to increase mindfulness. XR is an umbrella term that summarizes a variety of immersive technologies that provide computer-generated virtual objects, humans, or environments, and are characterized by a combination of real and virtual elements. The term is related to the reality-virtuality continuum of Milgram et al. (1995) and includes Virtual Reality (VR), Augmented Reality (AR), and Mixed reality (MR). In this paper, we use the terms XR or immersive media to reference immersive technologies in general. We use the term VR for systems that completely mask the physical world, and the term AR for systems that combine elements of the physical and virtual worlds. Human-XR-interaction is a segment of HCI research that deals with the perception and behavior of people in XR systems. While the work of Terzimehić et al. (2019) gives a broad insight into HCI-based mindfulness, they only include few XR-related research. Similarly, it remains unclear, whether the frameworks on digital mindfulness mentioned above are applicable for XR and whether XR interactions have the potential to match the criteria for mindfulness support.

2.3.1. Guidelines on XR-Based Mindfulness Support

While the above-mentioned frameworks are not specifically bound to XR interactions, Roo et al. (2017) developed a set of guidelines to support the design of XR-based mindfulness support. However, the proposed guidelines are closely related to those of Zhu et al. (2017) or Niksirat et al. (2019), with only a few guidelines specifically addressing XR-related design challenges. They too emphasize the importance of subtle guidance, while on the other side proposing the idea of challenging the user's focus via subtle distractors to train their ability to concentrate (distraction vs. guidance). In accordance with the idea of avoiding complex, judgment-provoking stimuli in mobile-based mindfulness interaction (Salehzadeh Niksirat et al., 2017; Niksirat et al., 2019), they stress that virtual environments in XR-based mindfulness support should be kept minimal and contribute to non-judgment. Also, similarly to the more general guidelines, they highlight that XR-based mindfulness support should avoid quantified performance feedback. They further address the idea of promoting acceptance via events that are out of the user's control and promoting autonomy by only including ambient information or feedback and allowing for exploration. The two guidelines of Roo et al. (2017) that apply most specifically to XR design are *using tangible interaction* and *choosing the right reality*. In order to ensure the focus on the user's own body they promote tangible interactions and haptic feedback. Additionally, they emphasize the importance of taking into account the user's personal traits concerning the perception of XR, for example the ability to distinguish reality and virtuality (suspension of disbelief, Heeter, 1992) or the tendency to suffer from simulation sickness.

2.3.2. Framework for XR Intervention Evaluation

Within other research topics, it has been shown that XR interactions can have a broad impact on human experience and behavior [e.g., anxiety therapy (Morina et al., 2015), discrimination experiences (Peck et al., 2013), involvement with nature (Ahn et al., 2016)]. Wienrich et al. (2020) presented a framework, *BehaveFIT*, that describes direct and indirect influences of VR interactions on human perceptions and behavior. They suggested three stages of influence: the presented content (*XR elements*), the corresponding perceptions and reactions, and the indirectly influenced attitudes and behavior decisions. They define VR via *virtual environment*, *virtual objects*, *virtual others*, and *virtual self-representation*. The XR elements subsume the visual, aural, or haptic execution, their behavior without the user's input, and the interactivity and reactions to user movements or actions. The corresponding perceptions on the other hand include the user's direct responses to these contents which on the one hand might include *XR-specific perceptions*, such as *sense of presence* (section 2.3.3) or *sense of embodiment* (section 2.3.6), and behavior-related perceptions and mental states, such as sense of space or time and current affects. Wienrich et al. (2020) emphasize the importance of including XR-specific perceptions into the analysis of XR-based influences on human perceptions and behavior in order to fully understand the mechanisms of XR interactions on psychological outcome variables. Finally, they address the influence of *individual characteristics* as well as *physical intervention settings* on the effect of XR interventions. Consequently, their framework offers a systematic description of immersive interventions that might also be important for XR-based mindfulness support. In the following we discussion immersion *per se*, as well as the four XR elements suggested by Wienrich et al. (2020) concerning their potential for XR-based mindfulness support.

2.3.3. Immersion and Presence

XR in general, and VR specifically, integrate well into the concept of digital mindfulness support by presence-with/presence-in (Zhu et al., 2017), particularly considering the concept of presence as the main defining characteristic of VR-specific perception. Conceptually, the virtual *sense of presence* describes a subjective state (Slater, 1999) which can be further separated into dimensions such as *place illusion*, and *plausibility illusion* (Skarbez et al., 2018) while the term *immersion* defines the "extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant" (Slater and Wilbur, 1997). In order to create immersion in a virtual environment, the medium should shield the user from their physical environment, the user's actions should lead to consequences in the virtual environment and, ideally, an immersive system should provide sensual information for different perception modalities (Slater, 1999). We consider immersion as a basic requirement for XR interactions. As it based on technical requirements, it is listed separately to the XR elements which refer to the provided content within an immersive system. Our analysis focuses on the content of XR-based mindfulness support. Thus, while we do acknowledge immersion as one potential of XR and refer to it in the effect synthesis, it is not included in our analysis of XR elements.

2.3.4. Virtual Environments

In an interview with mindfulness experts, Navarro-Haro et al. (2017) discovered, that imitations of nature might help experiencing mindfulness. On the other hand, abstract shapes can provide the possibility of exploring a meditative state (Du Plessis, 2017). Virtual environments provide a broad field of possibilities to create different emotional frames for a mindfulness experience. They can be visualized as naturalistic or artificial, provide abstract or figural backgrounds, and be enhanced by providing background sounds or haptic stimuli such as wind. Thus, as long as the foundations for immersion and thus presence are set, designing a virtual environment as a background for mindfulness support provides a variety of possibilities. Overall, the virtual environment can set the background for presence-in (Zhu et al., 2017) or exploration (Roo et al., 2017).

Within a virtual environment, XR offers a broad range of possibilities to design feedback in a subtle, subconscious way. As Zhu et al. (2017) and Salehzadeh Niksirat et al. (2017) suggest, (bio-)feedback should not be provided as a measure to quantify mindfulness but rather to design a meaningful background for mindful interactions. XR based mindfulness support give the opportunity to follow these instructions, e.g., by providing feedback peripherally or by creating ever-changing environments that adapt seamlessly to their current needs or states (e.g., Roo et al., 2017). However, it has not been systematically examined how virtual environments are designed in current research on XR-based mindfulness support, influence of different interpretations of feedback in XR on mindfulness and how they affect the state of mindfulness achieved by XR-supported mindfulness practice.

2.3.5. Virtual Objects

Even most simple virtual environments provide some kind of interactivity, such as visual movement information in the opposite direction to users' head movements, or tracking of gestures or body movements. Virtual objects create a new design space which offers a variety of possibilities and freedom in interaction design (Wienrich et al., 2017). Thus, the user might find new and curiosity arousing ways of interacting with objects. Further, as stated by Zhu et al. (2017) or Roo et al. (2017), tangible objects might be helpful in order to keep the focus on the user and their body while exploring a virtual environment. Thus, due to the diversity of virtual objects and interactions, they can easily be adapted to different guidelines of mindful interactivity. However, it remains open, how the possibilities of interactions with virtual objects are applied in current literature.

2.3.6. Virtual Self-Representation

Next to biofeedback within virtual environments and tangible object interactions, HCI offers interesting new ways to support full-body experiences outside of traditional yoga practice, mindful walks or body scan meditation. For example, Ståhl et al. (2016) introduced a full-body heat stimulation to subtly guide attention toward specific body parts without audio guidance. Further, (Niksirat et al., 2019) presented a digitally supported system for kinetic mindfulness practice, including movement tracking and smartphone-based feedback.

Within the field of XR, applications including a virtual self-representation offer much potential for body-related experiences. Similarly to the concept of immersion and presence, we distinguish between virtual self-representation as a visual, aural, and/or haptic depiction of the user within an XR system (avatar) and the subjective sense of embodiment as the corresponding XR-specific perception (Wienrich et al., 2020). As mentioned above, in mindfulness research the term *embodiment* or *embodied cognition* refers to the grounding of all experiences and feelings in the physical body (Wilson, 2002; Khoury et al., 2017). XR research adopts this concept and furthers it by introducing the *sense of embodiment* (Kilteni et al., 2012) or *virtual embodiment* (Roth and Latoschik, 2020), which describes the "conscious experience of self-identification (body ownership), controlling one's own body movements (agency), and being located at the position of one's body in [a virtual] environment (self-location)" (Roth and Latoschik, 2020). XR-based mindfulness support should carefully avoid interrupting the connection between the user and their body (Roo et al., 2017). Embodying a virtual self-representation within the virtual environment can help strengthen (Tajadura-Jiménez et al., 2012) or modify (Llobera et al., 2013) body perceptions and awareness. Consequently, the virtual self-representation leads to implications for the perception of the physical body (see Ratan et al., 2020 for an overview of the so called *Proteus effect*). While virtual self-representations thus provide the potential to include the body in an XR-based mindfulness support, it has not been analyzed systematically to what extent they are part of current research or how they impact on mindfulness.

2.3.7. Virtual Others

The representation of virtual others is comparable to the virtual self-representation. Virtual others can either represent other users of the XR system (avatars) or represent artificial interaction (agents). Interactions with virtual others can create social context and lead to an XR-specific perception, social presence (De Kort et al., 2007). The guidelines for digital mindfulness support mentioned above do not address interactions with other users. Nonetheless, the involvement of virtual others can be an opportunity, e.g., by using virtual agents as a reference for mindful behavior or by creating mindfulness-supporting interactions with other users. Here too, it has not yet been analyzed, whether and how virtual others are included in current XR-based mindfulness support and correspondingly whether impacts on mindfulness.

2.4. Outline of the Review

The topic of mindfulness has gained considerable attention in HCI research over the past decade. Various aspects of mindfulness and corresponding concepts have already been researched and summarized in this field. Terzimehić et al. (2019) provide an overview of how mindfulness is treated in HCI and which aspects of mindfulness are particularly emphasized in HCI research. While they mention XR interaction in their work, so far there does not exist a comprehensive overview of which aspects of mindfulness are already part of XR research.

Additionally, several authors so far have presented frameworks and guidelines toward creating digitally enhanced mindful interactions. XR systems offer many opportunities to meet those guidelines via the visual design, multimodal representation, and interactivity of the provided virtual environment, virtual objects, virtual self-representation or virtual others. Roo et al. (2017) listed a number of guidelines, which they applied to the design of XR-based mindfulness support. However, there has been no systematic research on the design of XR-based mindfulness support in current research and whether it meets those guidelines. Finally, it has not yet been summarized what effect different variations XR and its corresponding perceptions have on mindfulness. The current work bridges those research gaps by presenting the results of an analysis of the currently available literature on XR-based mindfulness support. The following research questions are addressed:

(I) What are the differences in the research of XR-based mindfulness support compared to the broader field of HCI mindfulness research?
(II) Which XR elements are used in current research on XR-based mindfulness support and do they meet the guidelines for digital mindfulness support?
(III) Which type of guidance, feedback, and tasks are included in current XR-based mindfulness support and do they support embodied mindfulness?
(IV) What effect does the design of XR elements have on mindfulness according to current research?

To answer the research questions I–III, the only constraint for the selection of papers was that they described any XR system designed to increase mindfulness. The analysis in research question IV included only articles that assessed the impact of XR-based mindfulness support in a pre-post design, comparing at least two experimental groups and including a subjective mindfulness measure. We did not restrict our analysis to a specific population.

Finally, we aimed for a model that combines the more general model for XR intervention design and evaluation, *BehaveFIT* described by Wienrich et al. (2019) with guidelines for the design of digital and XR-based mindfulness support. It further addresses the identified research gaps derived from the results of the review.

3. METHODS

We performed a structured literature review in which we included full-papers as well as short-papers. To get an overview of XR-related work in both HCI and psychology, we used two databases for the search: ACM Digital Library and U.S. National Institutes of Health's National Library of Medicine (PubMed). To ensure the completeness of our results, we cross-checked the resulting papers with another data base, APA PsycInfo. This search did not reveal further articles compared to the results of the former two. The review was conducted in accordance with PRISMA (Moher et al., 2011).

3.1. Search and Extraction

The search term was built as follows. We only included papers published between January 2010 and October 2020, that included both mindfulness-related and XR-related terms in their title or abstract. We searched for the following term: ["mindfulness" OR "mindful" OR "meditation" OR "meditative"] AND ["virtual reality" OR "VR" OR "augmented reality" OR "AR" OR "mixed reality" OR "MR" OR "XR" OR "immersion" OR "immersive"]. We included meditation in the search term, as it was most commonly used as a synonym to mindfulness in HCI research (Terzimehić et al., 2019).

The screening process was carried out in accordance with PRISMA guidelines and is depicted in **Figure 1**. In the first step, we combined the search results of both databases and excluded all duplicates. To narrow down our results to papers that matched our research aims, we manually screened the abstracts and excluded papers that (a) did not focus on mindfulness or mindfulness meditation, (b) did not include an XR system, or (c) were assigned as reviews or meta-analyses. In the next step, we further screened the full-text articles and excluded papers, which (a) did not investigate the influence of XR on mindfulness or mindfulness meditation outcomes, or (b) did not focus on mindfulness or mindfulness meditation. The resulting papers were assigned to two categories based on whether they included an effectiveness study addressing the impact on mindfulness or mindfulness-related outcomes (further mentioned as EMPIRIC, **Figure 1**, green area, right) or presented a new design for an XR-based mindfulness support without evaluation of mindfulness or mindfulness-related outcomes (further mentioned as DESIGN, **Figure 1**, green area, left). The total of these papers were included in the analysis to answer research questions I–III.

To answer research question IV we set up a list of eligibility criteria in accordance with PICOS (Methley et al., 2014). We only analyzed the papers classified as EMPIRIC. We did not restrict the participants to a specific population (P). Concerning the intervention (I), we included only papers where the XR interaction aimed to increase mindfulness. We excluded papers that did not compare the XR interaction to either a control group, a group that performed a mindfulness-supporting interaction without XR, or a group that performed a different version of the XR interaction (C). As an outcome variable we narrowed down the results to papers that included a subjective mindfulness measure (O). Finally, we only included papers that included a pre-post comparison of mindfulness (**Figure 1**, gray area, left). For additional analysis on whether the sense of presence was related to subjective mindfulness, we added a second analysis with papers that (O) in a subjective mindfulness measure as well as a measure of presence or embodiment and calculated a correlation between the two measures (**Figure 1**, gray area, right).

3.2. Analysis

To answer research question I, we analyzed the papers according to the framework developed by Terzimehić et al. (2019) which includes five dimensions: *lines of research*, *role*

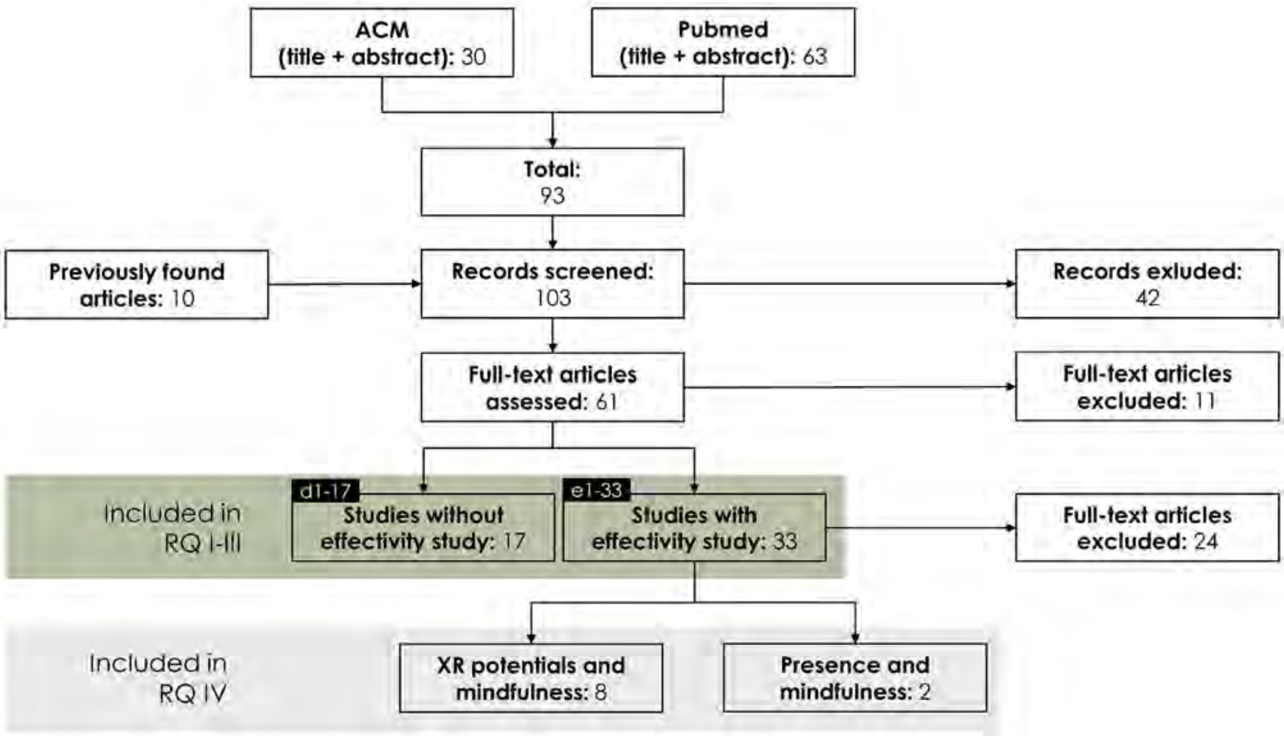

FIGURE 1 | Depiction of the PRISMA flow diagram (Moher et al., 2011). The chart shows the process of paper extraction. Fifty papers were included in the analysis of XR-based mindfulness support. Ten papers were included in the final effect synthesis.

of mindfulness, *type of mindfulness practice*, *longevity*, and *co-aspects of mindfulness*. Under the term *lines of research*, their framework divides mindfulness literature into research on meditation practice, therapy, mindfulness in interactions, reflection and knowledge gain, performance enhancement in other non-mindfulness-related tasks and meta-level research. *Role of mindfulness* divides research into papers that handle mindfulness as the goal of an interaction, as a way of being or as a mediator for other intervention outcomes, mainly used in therapy. The *type of mindfulness practice* can either be coded as formal, e.g., in guided meditations, or informal. In the dimension of *longevity*, research can be divided into papers that aim for short-term outcomes of XR-based mindfulness support and papers that aim for long-term changes in mindfulness. *Co-aspects of mindfulness*, addresses terms that frequently are used synonymous to mindfulness, such as meditation, reflection, therapy, or performance.

To answer research questions II, we relied on the work of Wienrich et al. (2020) and their framework of XR-based behavioral influences and divided the elements of XR (XR elements) into: *virtual environment*, *virtual objects*, *virtual self-representation*, and *virtual others*. For each of those categories, we analyzed whether the respective visual and non-visual representation, behavior and interactivity matched the criteria for mindful interactions. Based on the previous work on mindfulness interaction guidelines, we picked the following criteria. Concerning the virtual environments, we analyzed (a) the emotional framing, (b) the inclusion of figurative or abstract elements, (c) the visual clutter of the environment, (d) the visual detailedness of included elements, and (e) the usage of natural vs. human-made elements. For virtual objects, we analyzed whether they were instrumentalized, detailed, natural, or human-made and haptic or non-haptic. Concerning virtual self-representation and virtual others, we analyzed, whether they were humanoid or non-humanoid, full body representations or body parts, presented from 1st or 3rd person perspective, generic or personalized and interactive or non-interactive.

Concerning research question III we further analyzed whether the tasks and feedback used in the papers were in accordance with the guidelines of Salehzadeh Niksirat et al. (2017), Niksirat et al. (2019), and Roo et al. (2017) for interactive mindfulness tasks. We thus analyzed whether the systems (a) included body based interactivity, such as biofeedback or body movements, (b) included haptic or multi-modal feedback and guidance and (c) whether the feedback was presented peripherally and non-quantifiably. To prepare for the effect analysis, we further included the measured XR-specific perceptions (presence, embodiment, simulator sickness, or social presence).

For research question IV, we additionally included the specifications of the included independent variable, the subjective mindfulness measure and the measure of XR-specific perceptions. We then analyzed the results of these investigations on whether the tested conditions had an impact on (subjective) mindfulness, or whether the XR-specific perception was related to the subjective mindfulness measure.

4. RESULTS

The search within ACM Digital Library revealed 30 papers, duplicates excluded (PRISMA flow chart, **Figure 1**). The search within PubMed led to 63 articles, duplicates excluded. We added ten papers from our previous research that were not included in either of the databases or were published during the process of the review, leading to a total paper number of 103. Forty-two papers did not match our criteria and were thus excluded in the screening of abstracts. After screening the full-text articles of the remaining, we excluded eleven more papers. Further, we had to exclude one paper, which duplicated the data and results from another one leading to a number of $n = 50$ papers that were included in the analysis of research questions I–III. The split into EMPIRIC and DESIGN papers led to $n1 = 33$ EMPIRIC and $n2 = 17$ DESIGN papers. The further extraction of papers for research question IV led to a result of $n1 = 8$ papers that included a subjective mindfulness measure and $n2 = 2$ papers that included a comparison of mindfulness and subjective sense of presence.

As mentioned above, the following sections include both papers presenting XR-based mindfulness support systems or designs (DESIGN: $n = 17$) as well as papers that included an effectiveness study either on mindfulness or on therapeutic outcomes (EMPIRIC: $n = 33$). Within this section, the papers included in the review are referred to by an ID (EMPIRIC: e01–e23/ DESIGN: d01–d17) which relates to the result tables (**Table 1**). The results of our analyses are presented in **Table 2**, **Supplementary Tables 1–6**.

TABLE 1 | List of paper abbreviations.

ID	References	ID	References
d01	Chen et al. (2018)	e01	Lee and Kang (2020)
d02	Zaharuddin et al. (2019)	e02	Haisley et al. (2020)
d03	Gromala et al. (2011)	e03	Goldenhersch et al. (2020)
d04	Damen and Van der Spek (2018)	e04	Chavez et al. (2020)
d05	Auccahuasi et al. (2019)	e05	Kwon et al. (2020)
d06	Moseley (2016)	e06	Rice et al. (2018)
d07	Pendse et al. (2016)	e07	Kazzi et al. (2018)
d08	Patibanda et al. (2017)	e08	Botella et al. (2013)
d09	Seol et al. (2017)	e09	Gromala et al. (2015)
d10	Potts et al. (2019)	e10	Cheng et al. (2020)
d11	Bruggeman and Wurster (2018)	e11	Cikajlo et al. (2017)
d12	Choo and May (2014)	e12	Flores et al. (2018)
d13	Du Plessis (2017)	e13	Venuturupalli et al. (2019)
d14	Prpa et al. (2018a)	e14	Burton et al. (2013)
d15	Song et al. (2019)	e15	Navarro-Haro et al. (2019)
d16	Moseley (2017)	e16	Tarrant et al. (2018)
d17	Kosunen et al. (2017)	e17	Gomez et al. (2017)
		e18	Navarro-Haro et al. (2016)
		e19	Mistry et al. (2020)
		e20	Cebolla et al. (2019)
		e21	Prpa et al. (2018b)
		e22	Roo et al. (2017)
		e23	Paredes et al. (2018)
		e24	Chung et al. (2018)
		e25	Costa et al. (2020)
		e26	Tinga et al. (2019)
		e27	Salminen et al. (2018)
		e28	Min et al. (2020)
		e29	Costa et al. (2019)
		e30	Seabrook et al. (2020)
		e31	Navarro-Haro et al. (2017)
		e32	Kosunen et al. (2016)
		e33	Andersen et al. (2017)

4.1. The Role of Mindfulness in XR Mindfulness Research

Compared with the dimensions of HCI mindfulness research (Terzimehić et al., 2019), current EMPIRIC XR mindfulness research uses a rather narrowed definition of mindfulness (**Table A1**). The majority of EMPIRIC papers explored XR-based mindfulness support as a means to support therapy for a variety of psychological and physical disorders. Within these papers, mindfulness was mainly considered a mediator for the decrease of symptoms such as anxiety (e04, e05, e11–e17), stress or arousal (e04, e07, e11, e12, e25), or pain (e02, e08, e09, e13). Further, it was treated as a mediator for the increase of sleep quality (e01), general psychological health in elderly care (e10), concentration (e06), and positive affective states (e17, e18, e19). Most of the investigations instead included an evaluation of the short-term outcomes of one interaction (e02, e04, e07, e09, e12, e13, e16–e18). Consistent with the subordinate role as mediator for therapeutic outcomes, some of the therapeutic papers did not include a mindfulness measure in their analysis (e01, e02, e04–e06, e08, e09, e12–e14, e17–e19) but only measured the expected symptom reduction.

Also in EMPIRIC papers that investigated healthy participants, mindfulness was mainly used as a mediator for stress reduction (e23–e26) but also for anxiety (e28) and compassion toward others (e27). The other papers concerning research on XR-based meditation practice treated mindfulness as the main goal (e29–e33). Here, too, the focus was rather on short-term than on long-term XR-mindfulness outcomes (e20–e30, e32, e33). In accordance with the narrowed lines of research, most of the EMPIRIC papers used mindfulness synonymously with meditation (e01, e02, e04, e05, e07–e11, e13, e19, e22, e25–e26, e30, e32, e33), or therapy (e03, e12, e14, e17, e18) rather than focusing on mindfulness *per se* (e06, e15, e16, e20, e21, e23, e27–e29).

Compared to the EMPIRIC papers, the DESIGN papers rather focused on mindful meditation practice (d09–d17) and self-reflection (d06–d08) than on therapy (d01–d05). Accordingly, mindfulness was almost evenly mentioned as the main goal

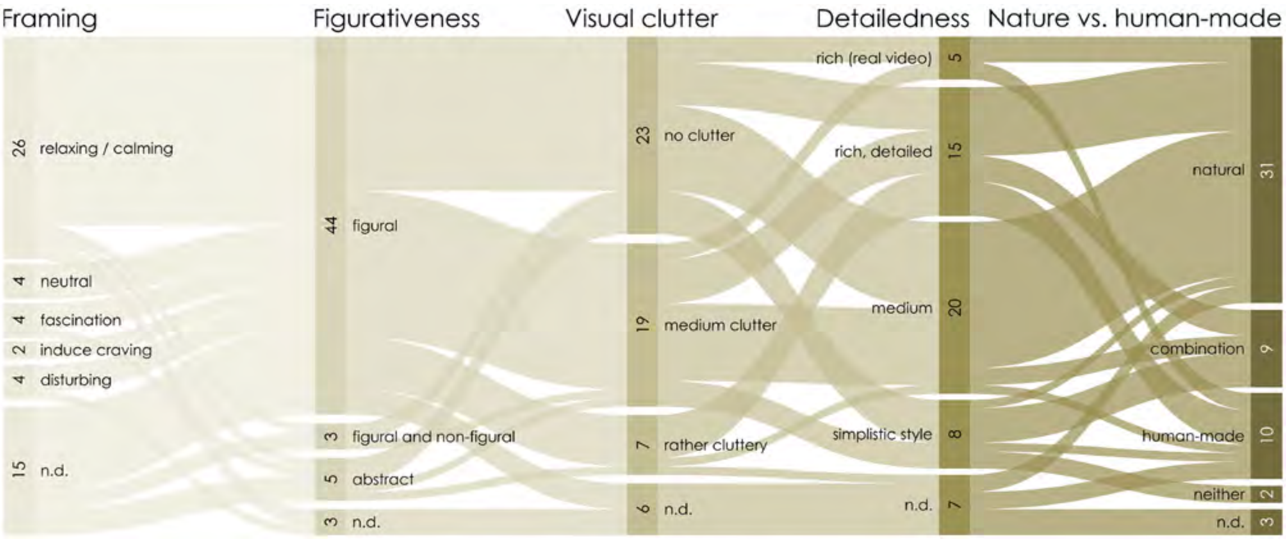

FIGURE 2 | Depiction of the different attributes of virtual environments used in the literature on XR-based mindfulness support. As some papers included different versions of virtual environments, the numbers here do not match the total number of papers.

(d06–d08, d13–d17) and as a mediator for other psychological or physical states (d01–d05, d09–d12). Additionally, two of the DESIGN papers focused on mindfulness in interaction (d09, d10).

4.2. The Role of XR-Elements in XR Mindfulness Research

Almost all of the EMPIRIC papers emphasized *immersion* as the most important property of XR-systems to support mindfulness. However, many of these papers did not specify, in which way immersion would be crucial for supporting mindfulness, e.g., whether the exclusion of external distractors, the surrounding nature of virtual environments or its vividness was the decisive factor. In the following sections, we describe how XR elements have been addressed in the current literature.

4.2.1. Types of Virtual Environments

The results of the analysis of virtual environments are depicted in **Supplementary Table 2** and **Figure 2**. The first factor we analyzed concerning the types of virtual environments used in current literature was the positive or negative framing of the experience. In most of the EMPIRIC papers, authors aimed for a relaxing, soothing, or generally calming environment (e1, e04, e06–e09, e11, e12, e15, e17, e18, e22, e23, e25–e29, e31, e33). The other EMPIRIC papers either aimed for a feeling of awe or fascination (e24) or did not define the framing of their environment (e02, e10, e13, e16, e19–e21, e30, e32). Four of the EMPIRIC papers included environments that aimed for negative framing. While e03 focused on the induction of craving via drug-related cues, e05, e06, and e14 included disturbing environments to contrast or challenge the user's mindfulness. In contrast to EMPIRIC papers, most of the DESIGN papers either described their environment neutrally or did not define the framing of the virtual experience (d03–d05, d08, d10, d13–d17). The DESIGN papers that described their environment as a possible framing either aimed for relaxing or calming effects (d02, d06, d11) or as well for the feeling of fascination and awe (d07, d12). The DESIGN papers as well did include environments to induce craving (d01) or anxiety (d09).

Concerning the general figurativeness of the environment, we analyzed whether the virtual environments in the literature included figurative and well-known patterns or objects or whether they relied on more abstract shapes. A majority of both EMPIRIC and DESIGN papers built their environments from figurative elements (e01–e06, e08, e10–e20, e22–e25, e27–e33; d01–d05, d07, d08, d10–d12, d17). While two papers included both figurative and non-figurative elements (fog) in their environments (e09, e21; d14), only five papers did not use any figurative elements (e24, e26; d13, d15, d16). Three of the papers did not include a detailed description of their environment (e07, d09) or did not define a specific environment but rather the possibility to build a variety of environments (d06).

Most of the EMPIRIC and DESIGN papers included environments, that either included only few elements or objects (e02, e03, e06, e08, e11, e20, e21, e23, e24, e26, e27, e29, e32, e33; d03, d05, d08, d10, d11, d14–d17) or included some more objects, but without inducing a high feeling of clutter (e04, e09, e11, e12, e13, e15, e17, e18, e19, e22, e23, e28, e30, e31; d02, d04, d07, d12, d13). Nevertheless, some of the EMPIRIC papers used rather cluttered environments, mostly on purpose, to contrast with more minimalistic environments or to induce an anxiety-related framing (e05, e06, e10, e11, e14, e16, e24).

While aiming for minimalism concerning the number of potential distractors within the environments, virtual environments in the EMPIRIC papers had a rich and detailed design (e04, e06, e09, e10, e16, e23, e24, e33), some of them using 360°-videos (e02, e03, e11, e20, e30), or at least had a medium amount of detail (e05, e06, e08, e11, e12, e15, e17–e19, e21, e22, e27, e29, e31). We rated only four of the EMPIRIC papers as simplistic and low-detailed (e13, e26, e28, e32). The virtual environments in DESIGN papers on the other hand were almost evenly rated as richly-detailed (d05, d11, d12, d13), medium detailed (d02-d04, d08, d14, d15), or simplistic (d01, d06, d09).

Finally, most of the EMPIRIC and DESIGN papers aimed for environments that were at least inspired by nature, including trees, water, beaches, grass, or mountains (e01, e02, e04, e08, e09, e11–e13, e15–e19, e21–e25, e29–e31; d02–d05, d08, d11, d14, d15). Only seven papers presented only human-made elements (e03, e05, e14, e20; d01, d10, d13). The other papers either included a combination of both nature-related and human-made elements (e06, e10, e27, e28, e32, e33; d07, d12, d17) or neither of them (e07, e26; d06, d09, d16).

In summary, the current literature predominantly uses positively framed, nature-inspired virtual environments. There is more emphasis on figuration, although there do exist some examples of how to design more abstract mindfulness-inducing environments. Additionally, our analysis shows that current literature uses predominantly non-cluttered environments that enable focus rather than challenging it. Nonetheless, the depicted virtual environments that are presented mostly are at least medium detailed rather than relying on simple shapes.

4.2.2. Types of Virtual Objects

The analysis of the interactive virtual objects is depicted in **Supplementary Table 3**. Only five papers included virtual objects (e10, e22, e28; d09, d10). Except for e22, which presented an AR system where the users explored and shaped augmented sand, all of these papers used figurative objects. In accordance with the generally rather detailed virtual environments, most of the presented virtual objects were rather detailed (e10, e22, e28, d09). While some of the objects clearly worked as tools for mindfulness-inducing interactions, such as aroma-therapy (e10) or gardening (d10), the other objects rather served as a possibility to explore the object or the user's own physical state (e22, e28, d09). The virtual objects that aimed for exploration were augmented and did include haptic stimulation.

4.2.3. Types of virtual Self-Representations

The analysis of virtual self-representations is depicted in **Supplementary Table 4**. Seven papers included a visual self-representation (e03, e20, e22, e28; d08, d09, d10). Except for d08, who designed a growing tree to represent the user, the self-representations were either designed as humanoid hands and arms (e03, e28, d09), perceived from first person perspective or a had full humanoid avatar, presented in first (d10) or third person perspective (e20, e22). While in e20 the users viewed themselves in a live video, the other papers did not use a personalized self-representation. Additionally, most of the virtual self-representations were responsive to the users actions, while some moved in accordance with the user's body movements (e20, e28; d09, d10), one of them grew and changed according to the user's current state (d08).

4.2.4. Types of Virtual Others

The analysis of papers that included a virtual others is depicted in **Supplementary Table 5**. Seven papers included virtual others (e06, e11, e14, e27, e32; d05, d17). All of these were designed humanoid and included either body parts (d05), an upper body (e11) or a full humanoid body (e06, e11, e14, e27, e32). Some of the virtual others were only presented visually and did not enable interaction (e27, e32; d05, d17). The others represented real humans and included the possibility to interact either verbally or non-verbally (e06, e11, e14, e17).

4.3. Guidance, Feedback, and Interactivity

The result of our analysis of the included sensory modalities, the types of guidance, the types of mindfulness tasks, the used input devices, and the types of feedback is depicted in **Supplementary Table 6**.

4.3.1. Inclusion of Multiple Sensory Modalities

As opposed to visual stimuli which were included in all papers, nine papers did not mention audio input either as background sounds or as verbal guidance (e14, e22, e23, e28; d05, d09, d10, d11, d15). The other papers mostly included visual and aural input, while five papers additionally included haptic (e20, e22, e28; d07, d09) or kinesthetic information (e10, e20, e22; d10).

4.3.2. Types of Guidance

Concerning the guidance of the user's focus (**Figure 3**), a majority of papers relied on vocal instructions (e02–e13, e15–e20, e25–e27, e29–e33; d01, d02, d04, d08, d12, d13, d17). While only two papers included text-based visual instructions (e10, e11), some of the other papers included visual or aural cues for focus guidance (e13, e27, e32, d09, d17). The other papers either did not describe the type of focus guidance they used or presented the instructions before the XR experience rather than including it (e01, e14, e21–e24, e28; d03, d05–d07, d10, d11, d14–d16).

4.3.3. Types of Mindfulness Tasks

The mindfulness-inducing tasks that were presented in the literature mostly included focusing the present moment. Some of those led the focus to the virtual environment (e08–e10, e12, e15–e18, e21–e24, e28–e32; d04, d14, d17). The papers that included tasks that led the focus to the user's body either included body scan meditations (e11, e32, d17, d05), the exploration of current sensations (e02, e08, e12, e15, e26, e30; d12, d15) or focus on breathing (e02, e08, e13, e25, e26, e29; d08, d11, d12). Only five papers included more active interactions within the virtual environment, either navigating through the environment (d02, d03, d04) or some kind of kinetic meditation (e20; d10).

4.3.4. Types of User Input

As indicated by the more passive tasks presented in most of the papers, no active input from the user was required in most of the tasks. The papers which included user input and respective feedback mostly relied on biofeedback, which either based on respiration (e13, e21, e22, e26, e27; d08, d11, d12, d14, d15), neural activity (e27, e32; d06, d10, d12, d13, d15, d17), heart tracking (e22, e28, d09, d15), or skin conductance (e09, d13). Seven papers instead required body movements. Those were divided into hand gestures (e10, e22; d15), eye movements (d04, d16), and full body movements (e20; d03, d10). Finally, one paper included the voice as input medium (e08). Here, users navigated through the environment by telling the experimenter where to move.

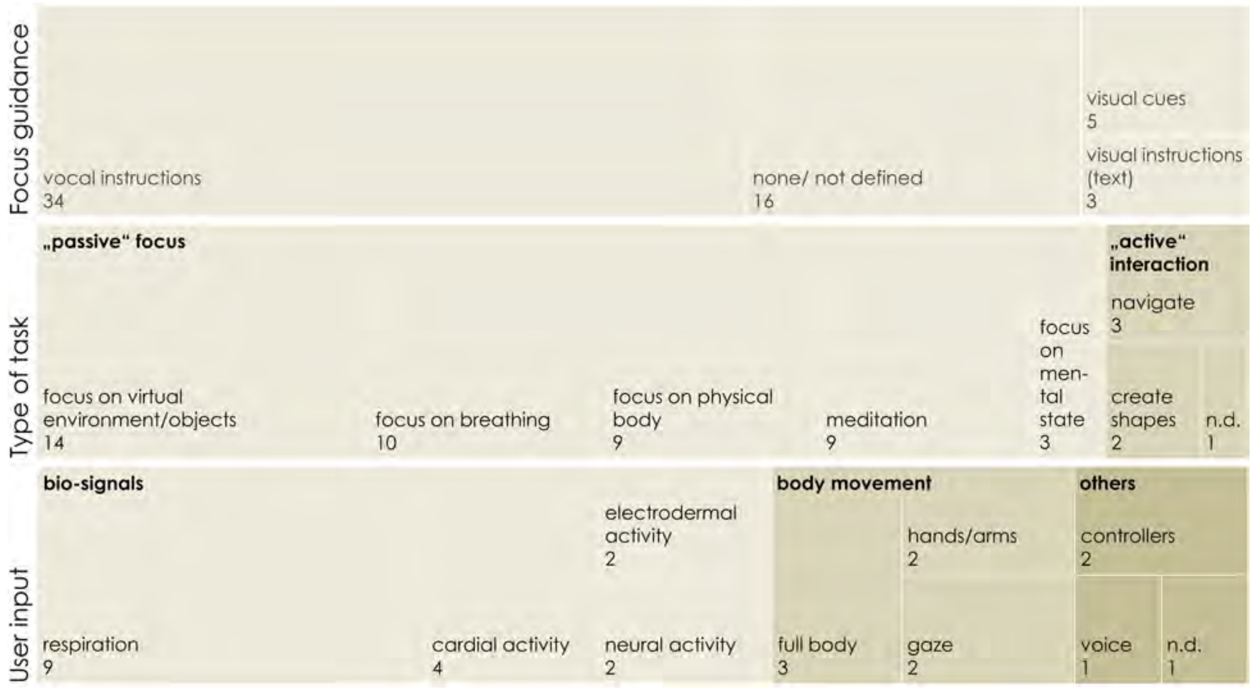

FIGURE 3 | Depiction of the different types of focus guidance, task descriptions, and user input. As some papers included different versions or combinations of guidance, tasks and user input, the numbers do not match the total number of papers.

4.3.5. Types of Feedback

More than half of the papers did not include feedback on user interactions or states other than tracking head movements. The systems that did include feedback (**Figure 4**) mostly used visual cues to provide it (e09, e13, e20–e22, e26, e27, e32; d02, d04, d08, d10–d17) and provided it either centrally in front of the user (e13, e20, e22, e26–e28; d04, d08, d09, d11, d16) or both centrally and peripherally (e21, e22, e32; d02, d04, d13–d15, d17). Only three papers presented visual feedback only peripherally (d10, d12, e09). Some of the papers additionally included haptic (e22, e28, d09) or aural feedback (e09, e13, e21; d10, d13, d14). The feedback was mostly provided via the virtual environment (e09, e21, e22, e26, e27, e32; d02, d04, d10–d17) or on virtual objects (e10, e13, e22, e28; d09, d16). Only a few papers included feedback that was presented on a virtual self (e20; d08) or other representations (e27). Most of the feedback was rated as non-quantified (e20–e22, e26, e28, e32; d02, d04, d08–d10, d13–d17).

In conclusion, XR-based mindfulness support in current literature mainly includes visual and aural input, with mostly based on vocal guided meditation which leads the focus to visually presented cues, to one's own breath or bodily sensations. Consequently, most of them either do not require active user input or rely on tracking bio signals which are fed back to the users, mostly visually, within the virtual environment.

4.4. Other Influencing Factors

Next to the XR elements, some of the papers included additional factors that might impact on the relation between XR-based mindfulness support and resulting mindfulness. These included individual user characteristics such as previous meditation experience (e11, e24), the type of meditation task within the virtual environment (e13) or the type of mindfulness measure (e13, e24).

4.5. Effect Synthesis

4.5.1. Manipulation of Immersion

The following section summarizes the results of the EMPIRIC papers that were included in the result synthesis. Only two of the papers that included a measure of an XR-specific perception calculated a correlative relationship between this measure, sense of presence, and *subjective meditation depth* as part of mindfulness (e25, e29). The meditation depth score used for this purpose (Piron, 2003) captures meditation depth on five dimensions: *hindrances*, *relaxation*, *transpersonal self*, *personal self*, and *transpersonal qualities* and additionally allows the specification of *general meditation depth*. In both papers there was a clear positive correlation between the result of the presence measure (SUS Presence Score, Slater et al., 1994) and the indicated meditation depth. In both papers, higher perceived presence was associated with a higher rating of perceived *transpersonal self* [$r = 0.5$ (e25) $r = 0.76$ (e29)] and *personal self* [$r = 0.47$ (e25), $r = 0.67$ (e29)]. While in the work of e25 presence was also moderately correlated to *hindrances* ($r = 0.52$), this relation was not revealed in the study of e29. Regarding the general meditation depth, a moderately positive correlation with presence was confirmed in both papers, $r = 0.52$ (e25), $r = 0.67$ (e29).

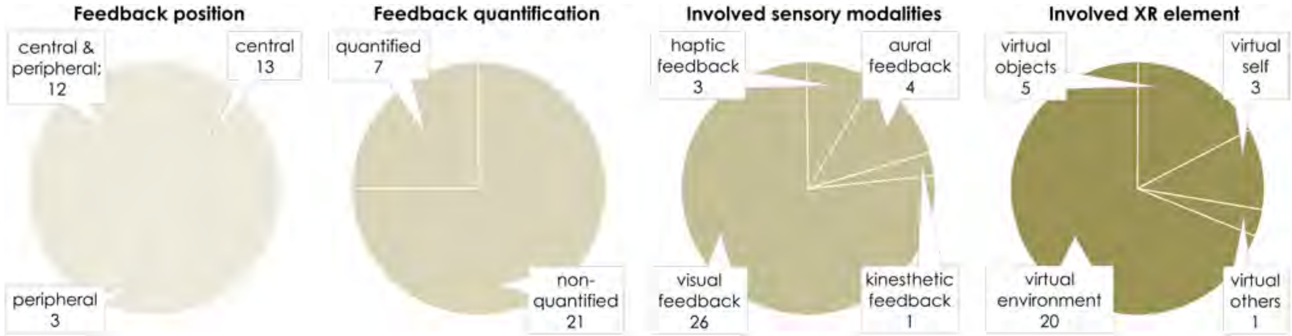

FIGURE 4 | Depiction of the different feedback types used in within the literature on XR-based mindfulness support. As not all papers included feedback and some papers included different feedback types, the numbers here do not match the total number of papers.

The results o the effect synthesis are depicted in **Table 2**. While in e10 a significant difference was found between a VR mindfulness intervention and a control group, the comparison between VR mindfulness interactions and non-mediated mindfulness training (e15, e33) led to less explicit results. In e15, a difference between immersive and non-immersive mindfulness was detected, but only on one dimension of the subjective mindfulness measure. In e33 immersive and non-immersive mindfulness training achieved a similar effect on the selected subjective mindfulness item. Compared to less immersive computer screens, as tested in e32 and e19, an immersive system led to higher mindfulness rankings than two-dimensional visual displays. However, e19 revealed sequencing effects demonstrating that the positive performance of the immersive medium occurred only when it was presented first.

The authors of e22 compared an AR and a VR system. Here, no effect of the medium on subjective mindfulness was discovered. However, it is unclear which of the two systems was more immersive, as in the AR condition more interactions with the augmented environment were possible while in the VR condition users meditated in a fully immersive system, but could not interact.

4.5.2. Manipulation of XR Elements

Only one paper recording subjective mindfulness compared different types of environmental representation (e23). In this study, dynamic and non-dynamic environments were compared. The authors did not find a significant impact of environmental dynamics on the perceived mindfulness of the participants (**Table 2**).

Regarding the representation of one's own body in the virtual environment, e20 was included in the results synthesis. Here, the participants perceived a real-time video of their own body from a new perspective and a virtual embodiment illusion was generated via embodiment exercises. However, the authors did not test whether the perceived embodiment toward the presented body had an influence on mindfulness. It was only shown that the virtual embodiment interaction did not have an influence on mindfulness compared to an unmediated meditation. This result was similar to the other two studies comparing an immersive mindfulness interaction with an unmediated one (e15, e33).

The authors of e32 investigated the effect of biofeedback on subjective mindfulness in comparison to a VR mindfulness tool without biofeedback. Here, the above mentioned effect of immersion compared to less-immersive presentation was found, but no difference was detected between a VR condition with and without biofeedback.

5. DISCUSSION

The present work aimed to analyze and identify (I) the differences in current research of XR to general HCI in mindfulness research, (II) the design of XR elements, (III) the design of XR-based mindfulness support, and (IV) the impact of XR design on mindfulness in current research. The analysis of along the dimensions of digital mindfulness support proposed by Terzimehić et al. (2019) showed that XR mindfulness research is still very limited compared to the general research on mindfulness in HCI. In particular, the research focuses on the therapeutic effects of VR mindfulness interventions, in which mindfulness serves mainly as a mediator between the virtual interaction and the targeted symptoms. Thus, current XR mindfulness research uses a rather narrowed, instrumental definition compared to the broader possibilities which impact mindfulness as proposed by Terzimehić et al. (2019).

The analysis of virtual environments, virtual objects, virtual self-representation, and virtual others used in current XR mindfulness research revealed, that here too, research has not yet reached the full potential of interactive XR-based mindfulness support. Frequently, immersion is suggested as an influencing factor without addressing its different facets. The most-used virtual environments are nature-inspired scenes or abstract structures, aiming for a sensation of calmness or awe. On the other hand, most of the XR experiences in current research neither include virtual objects, self-representation, or others.

Accordingly, only few papers address the possibilities of XR in more depth and present novel designs or active interactions. The tasks that are included in current literature are mainly based on focusing the virtual environment, or

TABLE 2 | Overview of the papers included in the effect synthesis.

ID	XR conditions	Mindfulness measure	Pre-post	Participants	Results pre-post	Results condition comparison
e15	(a) VR mindfulness task (b) Non-visualized mindfulness task	Five Facets of Mindfulness Questionnaire (FFMQ, Baer et al., 2008)	Yes	*N* = 33, age: *M* = 44.27, SD = 10.25 78.8% female no information on mindfulness practice	(a) Significant increase in three dimensions: describing (d = 0.85), awareness (d = 0.66), Non-judging (d = 0.55)	No significance test to compare conditions (b): less pre-post effects than (a) (dimension: non-judging)
e33	(a) VR mindfulness task (b) non-visualized mindfulness task	One-item scale (non-standardized)	No	*N* = 24, age: *M* = 22.1, SD = 3.3 25% female No information on mindfulness practice	—	No significant difference between (a) and (b)
e19	(a) VR mindfulness task (b) Computer screen mindfulness task	Meditative Experiences Questionnaire (MEQ, Frewen et al., 2011)	Yes	*N* = 96, age: 17–22 years 65.3% female 68.75% low/no mindfulness practice	—	Significant higher ratings in (a) compared to (b) significant sequence effects
e22	(a) VR mindfulness task (b) AR mindfulness task	Toronto Mindfulness Scale (TMS, Lau et al., 2006)	No	*N* = 12, age: *M* = 45, SD = 11 100% female 58% regular mindfulness practice	—	No significant difference between (a) and (b)
e10	(a) VR mindfulness task (b) Control group (no task)	Experiences of Mindfulness During Meditation scale (EOM-DM, Reavley and Pallant, 2009)	Yes	*N* = 60, age: *M* = 83.03, SD = 7.6 69% female no information on meditation experience	Significant increase in mindfulness experience	Significant group-time-interaction (control-group: no increase)
e32	(a) VR mindfulness task (b) Computer screen mindfulness task (c) VR mindfulness task with biofeedback	MEditation DEpth Questionnaire (MEDEQ, Piron, 2003)	No	*N* = 43, age: *M* = 28.7 60.4% female low/no mindfulness practice	—	Significant higher ratings in (a)/(c) compared to (b) no significant difference between (a) and (c)
e20	(a) VR embodied body swap (b) Non-visualized imaging	State Mindfulness Scale (SMS, Tanay and Bernstein, 2013)	Yes	*N* = 16, age: *M* = 30.56, SD = 10.86 75% female no regular mindfulness practice	Significant increase in both dimensions: mental events (d = 2.73) bodily sensations (d = 2.04)	No significant difference between (a) and (b)
e23	(a) Dynamic virtual environment (b) Static virtual environment	Toronto Mindfulness Scale (TMS, Lau et al., 2006)	No	*N* = 15, age: *M* = 38.4, SD = 16.7 46.7% female 40% regular mindfulness practice	—	No significant difference between (a) and (b)

the current state. The number of papers that include active, body-based interactions that might help focusing on the physical body is limited. Nonetheless, many papers in current literature at least focus on giving feedback on the user's bodily states. Biofeedback can be presented and perceived via various digital media. On the contrary, the XR element of self-representation and the XR-specific perception of virtual embodiment are unique to XR and raise new possibilities to support mindfulness via body-based feedback. However, embodying avatars as digital self-representation was only used in one paper.

The results synthesis reveals that a large proportion of current research has not tested the relationship between different XR elements and (subjective) mindfulness. However, initial results show that immersion *per se* within a non-interactive virtual natural environment only leads to a limited enhancement of mindfulness compared to conventional guided meditation tasks. However, due to the lack of research on more interactive systems, these results may only apply for XR systems with low interactivity and do not imply a low potential of XR-based mindfulness support *per se*.

5.1. XR-Based Mindfulness Support—Opportunity to Provide Presence-In?

5.1.1. Exploring Virtual Environments

As stated in the results, a large part of the papers mainly focuses on the recreation and presentation of natural scenes. Experiences in nature are closely linked to mindfulness (Zhu et al., 2017; Van Gordon et al., 2018). Thus, walking in a forest can be seen as a mindfulness inducing activity, providing natural *presence-in* (Zhu et al., 2017). However, it has not yet been researched whether an interaction with a virtual nature-themed environment has a similar effect on mindfulness as a real experience within nature. Some of the papers focused instead on more abstract environmental design, as abstract designs should increase curiosity toward the environment and give the opportunity to explore unknown shapes and terrains (Tinga et al., 2019) without judgment. Again, however, according to the current state of research, it remains open as to whether the postulated advantages of abstract virtual environments affect the state of mindfulness. Overall, hardly any studies have been conducted so far that researched the impact of different virtual environments on mindfulness. In comparison to real environments, XR enables to manipulate the environmental representation and behavior systematically. However, this potential has not been fully tapped so far.

5.1.2. From Guided Meditation to Interactive Mindfulness Interactions

As pointed out in section 4.3, there are only a few studies in which users actually interact with the virtual system, while the predominantly used tasks defined by vocally guided meditation within a calming environment. These results are in contrast to the work of Salehzadeh Niksirat et al. (2017), Niksirat et al. (2019), and Terzimehić et al. (2019) who emphasize the importance of interactivity and appropriate feedback within a digitally supported mindfulness practice. Both research groups address *slow design* (Grosse-Hering et al., 2013) as a design guideline for interactive mindfulness tasks. To actually evoke this interactive mindfulness, we propose that XR-based mindfulness support should consider kinetic interactions. Accordingly, the results of user interviews in Zaharuddin et al. (2019) emphasize the importance of interactions when creating mindful XR solutions. A first step in this direction are the systems of Potts et al. (2019) or Roo et al. (2017), that include active body movement. It would be interesting to examine to what extent the guidelines from research on slow design are applicable to XR and thus how active, kinetic XR interactions must be designed in order to support mindfulness.

5.1.3. Ambient Environmental Feedback

Besides the immersion in a mindfulness-inducing environment and the interaction with it, the presentation of biofeedback within the ambient environment is a great opportunity to provoke presence-in. Depending on its presentation biofeedback in XR serves less as a quantification of current state and more as a way to project the state of mind and make it perceptible in new, innovative ways. Similarly to general environmental representation, there are two branches of development here - embedding biofeedback in a naturalistic environment, and more abstract forms of representation. Future work here, similar to the general work on environmental representation, should address what kind of representation of virtual biofeedback has mindfulness-inducing effects.

5.2. Embodied VR—Opportunity to Provide Embodied Mindfulness?

Following on from immersive experiences, we proposed virtual self-representations and embodiment illusions as an opportunity to create embodied mindfulness experiences. While mindfulness is based on body perceptions (Heeter, 2016; Khoury et al., 2017; Niksirat et al., 2019), a regular mindfulness practice can increase interoceptive body awareness (Sze et al., 2010; Kühle, 2017) leading to an increased clarity, accuracy and immediacy in the perception and detection of body perceptions. The link between these two constructs is not yet reflected in the work on XR-based mindfulness support. Only one of the studies presented here included (subjective) body awareness as a dependent variable (Costa et al., 2019). The investigation of body sensations in XR within other research fields explores various interactions with one's virtual body, combining different visual, vestibular, and haptic stimuli to produce stimulation via sensory alignment or misalignment (Filippetti and Tsakiris, 2017; Czub and Kowal, 2019; Monti et al., 2020). In contrast, only one of the papers presented in our review used virtual embodiment illusions in XR and investigate their effects on mindfulness (Cebolla et al., 2019). Although some of the papers highlighted the importance of including the user's body (Roo et al., 2017), many researchers have not yet drawn the conclusions and implemented a virtual self-representation. Future work should address whether a virtual self-representation can promote mindfulness in XR. It should further investigate the type of self-representation, whether a realistic avatar is mandatory or whether a modified, enhanced or individualized virtual self-representation has a positive influence on XR-based mindfulness support. Similarly to the interactivity of the objects in an XR-based mindfulness support, it should be researched which kind of interaction with the own virtual body can be useful.

5.2.1. XR-Specific Perceptions and Mindfulness

In addition to the direct influences of the different XR elements on mindfulness, it is worth mentioning that only a few of the presented studies examined to what extent the proposed XR-based mindfulness support affected the XR-specific perception itself. XR research usually investigates whether the experience in a virtual environment is accompanied by a sense of presence, whether the embodiment of an avatar leads to a sense of embodiment, or whether the presentation of virtual others leads to a sense of social presence. Thus, they can be seen as a kind of indicator as to whether the content of a virtual experience had these desired effects. An interesting research question would therefore be not only whether different XR conditions had an influence on mindfulness, but also whether and to what extent mindfulness is related to common XR-based phenomena.

5.3. Framework for XR-Based Mindfulness Support

Based on our literature analysis and the existing frameworks and guidelines on digital mindfulness support (Salehzadeh Niksirat et al., 2017; Zhu et al., 2017; Niksirat et al., 2019), XR-based mindfulness support (Roo et al., 2017), and XR intervention evaluation (Wienrich et al., 2020), we propose a framework for

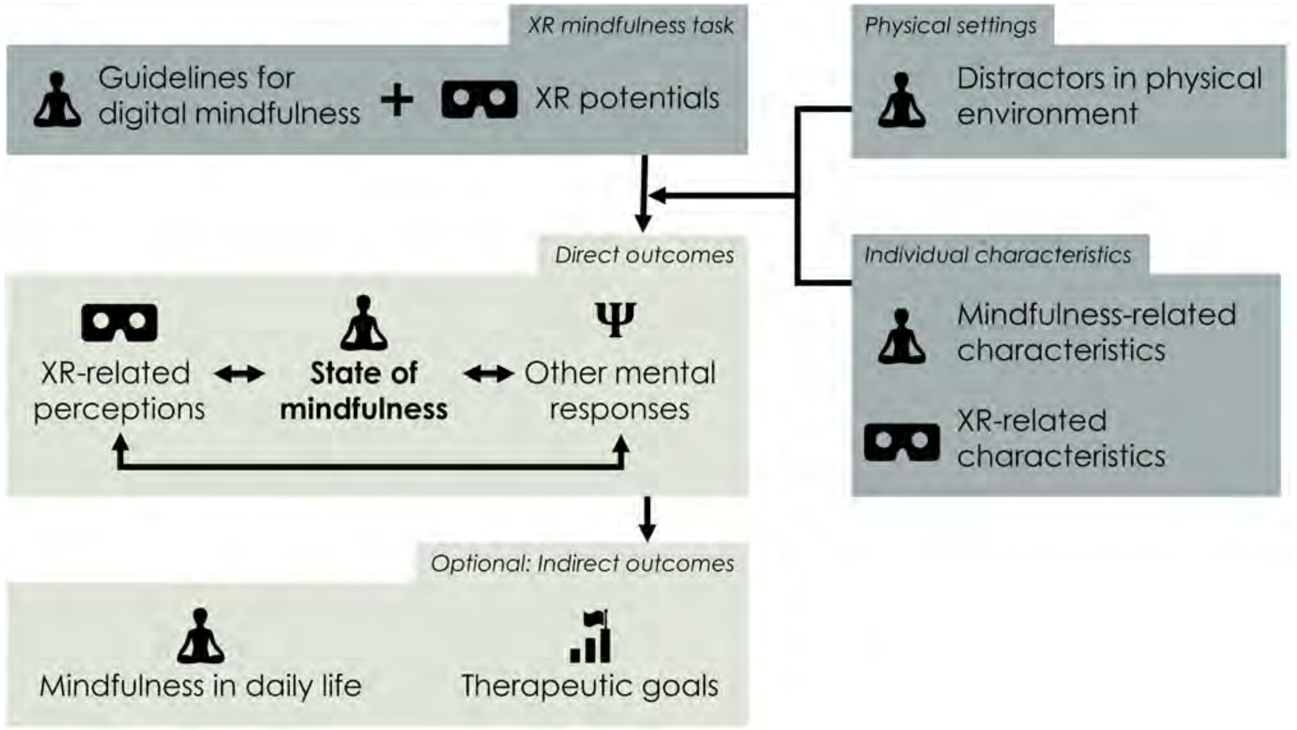

FIGURE 5 | Framework of the influence of XR elements on mindfulness and mindfulness-related concepts. The darker boxes include variables that impact or moderate the outcomes of our interactions. The lighter boxes represent the outcomes, divided into direct responses to the XR experience and indirect target outcomes.

design and evaluation of XR-based mindfulness support. Using the modifiable XR elements and the guidelines for mindful interaction, we can create interactions that take into account the constraints and possibilities of XR, and meet the requirements for mindful interactions. The result is shown in **Figure 5**.

5.3.1. Design of a XR-Based Mindfulness Task

The first level of the framework, *XR mindfulness task*, summarizes a set of *guidelines for digital mindfulness support*. We distinguish between guidelines for general design, focus guidance, feedback, and user input. The resulting guidelines are depicted in **Table 3**. While some of the guidelines focus on designing the XR elements in a specific manner, e.g., minimalistic instead of complex, others focus on the inclusion of different elements, e.g., focus-enabling as well as challenging elements, multiple sensory cues, or body- and mind-based interactions.

These guidelines can be applied to the four XR elements (Wienrich et al., 2020): (a) virtual environment, (b) virtual or augmented objects, (c) virtual body and self-representation, and (d) virtual others. The combination of those XR elements and the guidelines for digital mindfulness support leads to a number of possible research questions which can help approaching future research systematically and defining design guidelines for each of the XR elements. **Figure 6** gives a short overview of the design space and exemplary research questions within each of the elements and guideline categories. Since the empirical results so far are not sufficient to create a complete set of design guidelines, the overview is limited to some sample questions.

Not every XR-based mindfulness support needs to include all of the XR elements. Nevertheless, the overview offers the possibility to choose the XR element best suited to the respective task or goal. Thus, the different elements are helpful in implementing the guidelines for mindful interaction in different ways: environmental representation is well-suited to showing peripheral biofeedback, without being instrumentalized. Virtual objects may be more likely to assist in facilitating body sensations via soft haptic feedback. While an interactive virtual self-representation might help understanding bodily consequences, virtual others might be included to enable focus by leading as an example.

5.3.2. Mindfulness as Target Outcome: Related Concepts

To examine the effects of an XR-based mindfulness support, it is necessary to consider the second stage of the framework, *direct outcomes*, that might be related to the *state of mindfulness*. Although mindfulness was not the main goal in some of the literature, we still claim the importance of examining the influence of an XR-based mindfulness support on state mindfulness. Therefore, the *state of mindfulness* forms the center of our framework. As proposed in Terzimehić et al. (2019) state mindfulness can be measured in various ways,

TABLE 3 | Guidelines for mindfulness task design (derived from: (Zhu et al., 2017; Salehzadeh Niksirat et al., 2017; Roo et al., 2017; Niksirat et al., 2019).

	Guidelines: choose
General design	Minimalism instead of complexity
	Multimodality instead of unimodality
	Enabling and/or challenging elements
Guidance	Subtle instead of direct guidance
	Peripheral instead of central guidance
	Sensory cues instead of vocal guidance
Feedback	Soft instead of direct feedback
	Non-quantified instead of quantified feedback
	Peripheral instead of central feedback
	Predictable and non-predictable elements (acceptance)
Interaction	Active and passive interaction
	Body-based and mind-based interaction
	Explorative instead of instrumentalized interaction
	Slow and repetitive interactions

for example via physiological measures (Bostanov et al., 2018), subjective scales (Bergomi et al., 2013), or movement detection (Salehzadeh Niksirat et al., 2017).

To analyze the mechanisms of XR-based mindfulness support, we further list *XR-specific perceptions* and their relation to mindfulness, which can be measured via subjective scales: sense of presence(e.g., IPQ, Schubert et al., 2001), sense of embodiment (e.g., VEQ, Roth and Latoschik, 2020), sense of social presence (e.g., SPGQ, De Kort et al., 2007), and simulation sickness (e.g., SSQ, Kennedy et al., 1993). In addition, *other mental responses* that are generally associated with mindfulness and their relationship to XR-specific perceptions can be considered. In contrast to the XR-specific perceptions, there is data from psychological research that deals with how mindfulness is related e.g., to emotion regulation (Feldman et al., 2007), cognition (Zeidan et al., 2010), or stress (Kabat-Zinn, 2003). The second level of the framework thus arises a second set of possible research questions addressing the current research gap concerning the relation of mindfulness to XR-specific perceptions and other mental responses.

5.3.3. Mindfulness as Mediator: Indirect Outcomes

In most of the EMPIRIC studies, mindfulness was used as a mediator for other, mostly therapeutic goals. Some other studies not only considered state mindfulness, but examined whether XR-based mindfulness support can have a longer-term impact on mindfulness in daily life. Therefore, we add a third level to the framework, *indirect outcomes*. Since some of the studies only examined the impact of the XR interaction on these targets, we want to highlight here that for a full understanding of the mechanisms of an XR-based mindfulness support it is important to also consider the role of state mindfulness and other, XR-based mindfulness support, as mediators of these outcomes.

5.3.4. Moderating Effects of Physical Surroundings and Individual Characteristics

Another point is the moderating influence of *individual characteristics*, as highlighted by Wienrich et al. (2020). The former addresses the ability to distinguish reality and virtuality or the tendency to perceive simulation sickness. The latter includes for example trait mindfulness or experience with mindfulness practices. The physical setting of an XR interaction can affect the choice of the appropriate medium and its effects on mindfulness. While in a noisy or busy environment VR helps with masking, in a quiet setting AR-systems might be more appropriate to create mindful exploration.

5.4. Limitations

While our paper provides new insights into current research and research gaps on XR-based mindfulness support, the results are limited in a few ways. First, it can be argued that the strong therapeutic focus of the EMPIRIC papers underlies the selected database. Of course, PubMed certainly provides some therapeutic bias. However, we conducted a scanning procedure across several other psychological databases which did not reveal any additional papers to our initial search.

As described in section 3, we did not analyze the impact of the design of XR-based mindfulness support on usability, user experience or user acceptance which were addressed in some of the DESIGN as well as some EMPIRIC papers. The focus of this work was to describe the XR elements in current mindfulness tasks and their impact on mindfulness and mindfulness-related outcomes. Nevertheless, an analysis of these more practical topics could give broader insights into the design possibilities of XR-based mindfulness support and should be included in future analyses. Additionally, we limited our effect analysis to papers that included subjective measures of mindfulness and did not extend it to papers with physiological measures, as we wanted to make sure that the effects were actually related to mindfulness. Commonly recorded physiological measures such as skin conductance and heart rate are not specific to mindfulness or the valence of the psychological state but might be more indicative of the level of arousal, or a calming or relaxing effect (Costa et al., 2019; Tinga et al., 2019) of the interaction. Future work should nevertheless address whether and how XR-based mindfulness support has an influence on physiological mindfulness measures and how these can be distinguished from general influences of XR on physiological measures (e.g., distortion of EEG data, Hertweck et al., 2019).

In section 2.2.3, we emphasized that the concept of (embodied) mindfulness is closely related to that of body awareness. The current review did not yet include body awareness *per se*, as the focus was on initially analyzing current XR-based mindfulness support. Future work could address the extent to which XR-based mindfulness support is related to body awareness, or on the other hand the extent to which XR body awareness tasks are associated with a change in mindfulness.

	General Design • Minimalism • Multimodality • Enabling and/or challenging elements	Guidance • Subtle guidance • Peripheral guidance • Sensory cues	Feedback • Soft • Non-quantified • Peripheral • Partly unpredictable	User Input • Active and passive • Body-based and mind-based • Exploratory • Slow and repetitive
Virtual Environment • Sensory representation • Behavioral representation	Which kind of **virtual background** facilitates/challenges mindfulness?	Which kind of **environment-based guidance** facilitates/challenges mindfulness?	Which kind of **environment-based feedback** facilitates/challenges mindfulness?	Which input modality fits mindful interactions with the **virtual environment**?
Virtual Objects • Sensory representation • Behavioral representation	Which kind of **virtual objects** facilitate/challenge mindfulness?	Which kind of **object-based guidance** facilitates mindfulness?	Which kind of **object-based feedback** facilitates mindfulness?	Which input modality fits mindful interactions with **virtual objects**?
Virtual Self • Sensory representation • Behavioral representation	Which kind of **self-representation** facilitates/challenges mindfulness?	Which kind of (virtual) **self-based guidance** facilitates mindfulness?	Which kind of **self-based feedback** facilitates mindfulness?	Which input modality fits mindful interactions with a **virtual self**?
Virtual Others • Sensory representation • Behavioral representation	Which kind of **virtual others** facilitate/challenge mindfulness?	Which kind of (virtual) **other-based guidance** facilitates mindfulness?	Which kind of **other-based feedback** facilitates mindfulness?	Which input modality fits mindful interactions with **virtual others**?

FIGURE 6 | Overview of the combinations of design guidelines for digital mindfulness support and the XR elements.

5.5. Conclusion

Mindfulness is a topic that has received increasing attention in HCI over the last decade. In the field of XR, several researchers have discussed the potential of XR-based interactions support. The present paper provides a systematic analysis of the current literature with regard to the influence of different XR contents on mindfulness. The results of our review show that XR mindfulness research has so far focused on mindfulness in a rather limited way. The analyzed papers had mainly therapeutic orientation and treated mindfulness as a mediator for other mental and physical perceptions. Additionally, we revealed that so far a rather limited fraction of XR elements have actually been researched for their influence on mindfulness. Current empirical work predominantly uses vocally guided meditation, in which neither the user's body nor interactivity with the XR system are involved. The analysis of the results indicated that currently examined XR-based mindfulness support systems hardly have a positive influence on mindfulness compared to conventional meditation. However, recent developments in technology and design show potential for more powerful XR-based mindfulness support. Our framework is a structured approach to define the design space for XR-based mindfulness support. It combines design guidelines for digital mindfulness support with the elements and mechanisms of XR interventions leading to a variety of research questions and the possibility to create new, XR-specific design guidelines for mindful interactions. As a result, it enables to systematically close research gaps and get a comprehensive picture of XR-based mindfulness support.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

ND and CW contributed to the conception of the literature analysis and the manuscript and wrote sections of the manuscript. ND organized and performed the analysis. MEL supervised the structuring of results. MEL and CW supervised the paper writing process.

FUNDING

This research has been funded by the German Federal Ministry of Education and Research in the project ViTraS (project number 16SV8219). This publication was supported by the Open Access Publication Fund of the University of Würzburg. We thank Roland Zechner for table and figure formatting.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.644683/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

A. APPENDIX

TABLE A1 | Tasks, user input, and feedback presented in the papers with interactive mindfulness tasks.

ID	Task	User input	Feedback
d02	Navigate through environment	Controllers	Virtual locomotion
d03	Navigate through environment	Bio data: not defined Motion: full body	Virtual locomotion
d04	Focus on virtual objects and navigate through environment	Motion: gaze	Virtual locomotion
d08	Focus on breathing and keep posture	Bio data: respiration	Expansion and contraction of tree trunk; expansion of colors; and blooming with changing breath rhythm
d09	Focus on virtual objects	Bio data: cardial activity	Pulses synchronized with heart beat
d10	Shape environment	Bio data: neural activity Motion: full body	Blooming flowers and ambient sounds
d11	Focus on breathing	Bio data: respiration	Sparkling dots in a tree
d12	Focus on breathing and physical body	Bio data: respiration and neural activity	Opening flowers
d13	Meditation	Bio data: neural activity and electrodermal activity	Changing movement patterns
d14	Focus on virtual environment	Bio data: respiration	Control of position above ocean, movement of clouds
d15	Focus on mental state	Bio data: neural activity and cardial activity Motion: hands/arms	Change in colors and shapes of the environment
d16	Not defined	Motion: gaze	Triggering events by focusing objects
d17/e32	Focus on physical body and virtual objects	Bio data: neural activity	"Energy bubble" surrounding the user becomes more visible; platform movement signalling concentration
e08	Focus on breathing and virtual objects	Voice	Virtual locomotion
e09	Focus on virtual environment	Bio data: electrodermal activity	Increased/reduced intensity of fog
e10	Focus on virtual objects	Controllers	Object movement
e13	Focus on breathing and physical body	Bio data: respiration	Adjustment of audio prompts, outward-moving, growing blue particles
e20	Focus on physical body	Motion: full body	Mirroring of body movements
e21	Focus on virtual environment	Bio data: respiration	Control of position above ocean movement of clouds
e22	Shape environment; focus on virtual environment;	Bio data: respiration and cardial activity	Changed topology; moving sea, changing weather and landscape
e26	Focus on breathing	Bio data: respiration	Growing/shrinkage of a white cloud
e27	Meditation (empathy)	Bio data: respiration and neural activity	Illumination of panels on the virtual floor; growing/shrinkage of shining circles around statues
e28	Focus on virtual objects	Bio data: cardial activity	Pulses synchronized with heart beat

2 Resize Me! Exploring the User Experience of Embodied Realistic Modulatable Avatars for Body Image Intervention in Virtual Reality.

Döllinger, N., Wolf, E., Mal, D., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022). Resize me! Exploring the user experience of embodied realistic modulatable avatars for body image intervention in virtual reality. *Frontiers in Virtual Reality, 3*. doi: 10.3389/frvir.2022.935449

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Author Contributions

Nina Döllinger and Erik Wolf jointly conceptualized large parts of the experimental design, collected the data, designed the interaction techniques, and took the lead in writing the manuscript. Nina Döllinger provided the contributions to user experience evaluation and body awareness-related parts and conducted the qualitative data analysis. Erik Wolf provided the contributions on body weight perception and methodology and performed the quanti- tative data analysis. Erik Wolf and David Mal developed the Unity application, including the experimental environment and avatar animation system. Erik Wolf implemented the in- teraction techniques for body weight modification. Mario Botsch and Stephan Wenninger provided the framework for the reconstruction of the avatars as well as their integration and realistic body weight modification in Unity. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript [1].

[1]The author contributions of the original paper were refined in the course of the dissertation to highlight each author's contribution further

TYPE Original Research
PUBLISHED 11 October 2022
DOI 10.3389/frvir.2022.935449

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Virtual Reality and Human Behaviour, a section of the journal Frontiers in Virtual Reality

RECEIVED 09 June 2022
ACCEPTED 04 August 2022
PUBLISHED 11 October 2022

CITATION
Döllinger N, Wolf E, Mal D, Wenninger S, Botsch M, Latoschik ME and Wienrich C (2022), Resize Me! Exploring the user experience of embodied realistic modulatable avatars for body image intervention in virtual reality.
Front. Virtual Real. 3:935449.
doi: 10.3389/frvir.2022.935449

Resize Me! Exploring the user experience of embodied realistic modulatable avatars for body image intervention in virtual reality

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Obesity is a serious disease that can affect both physical and psychological well-being. Due to weight stigmatization, many affected individuals suffer from body image disturbances whereby they perceive their body in a distorted way, evaluate it negatively, or neglect it. Beyond established interventions such as mirror exposure, recent advancements aim to complement body image treatments by the embodiment of visually altered virtual bodies in virtual reality (VR). We present a high-fidelity prototype of an advanced VR system that allows users to embody a rapidly generated personalized, photorealistic avatar and to realistically modulate its body weight in real-time within a carefully designed virtual environment. In a formative multi-method approach, a total of 12 participants rated the general user experience (UX) of our system during body scan and VR experience using semi-structured qualitative interviews and multiple quantitative UX measures. Using body weight modification tasks, we further compared three different interaction methods for real-time body weight modification and measured our system's impact on the body image relevant measures body awareness and body weight perception. From the feedback received, demonstrating an already solid UX of our overall system and providing constructive input for further improvement, we derived a set of design guidelines to guide future development and evaluation processes of systems supporting body image interventions.

KEYWORDS

virtual reality, avatar embodiment, user experience, body awareness, body weight perception, body weight modification, body image disturbance, eating and body weight disorders

1 Introduction

Obesity is a complex chronic disease characterized by severe overweight and an above-average percentage of body fat (World Health Organization, 2019). Its prevalence has more than doubled within recent decades and is expected to rise (Venegas and Mehrzad, 2020; World Health Organization, 2021). Besides the physical burdens (e.g., an increased risk of several secondary diseases (Stefan et al., 2021), affected individuals deal with an external or internalized stigmatization that can lead to body image disturbances (Thompson and Tantleff-Dunn, 1998; Rosen, 2001; Meadows and Calogero, 2018). Body image disturbances are composed of a misperception of body dimensions (body image distortion) and the inability to like, accept, or value one's own body (body image dissatisfaction) and are also associated with a reduced body awareness (Todd et al., 2019b; Turbyne et al., 2021). Various interventions (e.g., cognitive-behavioral therapy supported by mirror exposition or fitness training) have been designed to target persisting disturbances but often only achieve small improvements in the body image (Alleva et al., 2015). In recent years, novel virtual reality (VR)-based methods complementing the therapy of body image disturbances have successfully been explored in research with promising results (Ferrer-Garcia et al., 2013; Wiederhold et al., 2016; Riva et al., 2019). The further improvement of these approaches in the context of obesity forms the frame of our current work.

VR-based approaches for supporting body image interventions often use 3D models of human beings (Horne et al., 2020; Turbyne et al., 2021), so-called avatars (Bailenson and Blascovich, 2004). VR in general, and the confrontation with embodied avatars in particular, have great potential to influence human perception and behavior (Yee and Bailenson, 2007; Ratan et al., 2020; Wienrich et al., 2021). In the context of body image, avatars have been utilized to expose users of a VR system to generic virtual bodies or body parts varying in size or shape to investigate the principles of body weight perception (Thaler, 2019; Wolf et al., 2020, 2021, 2022a) or to influence the perception or attitude towards the user's own body (Turbyne et al., 2021). Recent developments in computer graphics allow for the generation of photorealistic avatars that match a person's real-life appearance within a short duration at a low-cost (Achenbach et al., 2017; Wenninger et al., 2020; Bartl et al., 2021) and for a realistic modulation of body dimensions in pictures and videos (Zhou et al., 2010; Zhao et al., 2018; Xiao et al., 2020; Tang et al., 2021) or in VR (Piryankova et al., 2014a; Hudson et al., 2020; Maalin et al., 2020). However, no work has yet been presented where users embody their photorealistically personalized avatar in VR while also having the ability to manipulate that avatar's body shape in real-time actively, nor has the impact of such a system on the users and their experiences been evaluated.

To address this gap, we present the development of a VR system allowing users to embody a photorealistic, personalized avatar within a virtual environment and to actively modify its body weight in real-time using different interaction methods. In a further step, we evaluated the system with regard to a later usage in clinically relevant settings within our research project Virtual Reality Therapy by Stimulation of Modulated Body Perception (ViTraS) (Döllinger et al., 2019). In particular, we performed a formative user evaluation of the avatar generation process and interactive VR exposure with a small sample of healthy participants. Following Wienrich and Gramlich (2020) and considering the future potential user group, we assessed relevant factors such as security, physical comfort, accessibility, usability, and user experience, which we also already considered during the development process. Based on our evaluation's results, we derive a set of design guidelines for the future design and development of similar avatar-based body image therapy support tools.

2 Related work

Body image disturbance is characterized by an "excessively negative, distorted, or inaccurate perception of one's own body or parts of it" (World Health Organization, 2019). It may manifest in body image distortion, the misperception of one's body weight and dimensions that have repeatedly been reported based on underestimations (Valtolina, 1998; Maximova et al., 2008) or overestimations (Docteur et al., 2010; Thaler et al., 2018a), or body image dissatisfaction, a negative attitude towards the body that is associated with body image avoidance (Walker et al., 2018) and reduced body awareness (awareness for bodily signals) (Peat and Muehlenkamp, 2011; Todd et al., 2019a,b; Zanetti et al., 2013). While often caused by internalized weight stigma and a fear of being stigmatized by others (Meadows and Calogero, 2018), body image disturbance interferes with efforts to stabilize body weight in the long term (Rosen, 2001). Treatments for body image disturbance mainly rely on cognitive-behavioral therapy, typically combining psychoeducation and self-monitoring tasks, mirror exposure, or video feedback (Farrell et al., 2006; Griffen et al., 2018; Ziser et al., 2018). Based on the fundamentals of these established methods, an increasing number of researchers have started to explore VR applications as additional support for attitude and behavior change in general (Wienrich et al., 2021) and therapy of body image disturbance (Riva, 1997; Ferrer-Garcia et al., 2009, 2013; Riva et al., 2019; Turbyne et al., 2021) and obesity in particular (Döllinger et al., 2019; Horne et al., 2020).

2.1 The unique potential of modulatable avatars in VR

VR offers the opportunity to immerse oneself in an alternative reality and experience scenarios that are otherwise only achievable via imagination. Endowed with this unique power, mainly the use of avatars has attracted attention in treating body image disturbance (Horne et al., 2020; Turbyne et al., 2021). Image processing methods for simulating body changes are well established. Using parametric models, it is possible to retouch images to simulate different face or body shapes (Zhou et al., 2010; Zhao et al., 2018) and even manipulate them in real-time during video playback (Xiao et al., 2020; Tang et al., 2021). Avatars in VR allow simulating rapid changes in body shape or weight in an immersive environment using life-sized avatars going beyond the presentation of pictures and videos. They enable further general investigation of body weight perception (Thaler, 2019; Wolf et al., 2020, 2021). While some researchers are using multiple generic avatars differing in body weight (Normand et al., 2011; Piryankova et al., 2014b; Keizer et al., 2016; Ferrer-Garcia et al., 2018; Preston and Ehrsson, 2018), others have developed methods for dynamic body weight modification in VR (Alcañiz et al., 2000; Johnstone et al., 2008; Piryankova et al., 2014a; Nimcharoen et al., 2018; Hudson et al., 2020; Maalin et al., 2020; Neyret et al., 2020). A huge advantage when using advanced body weight modification methods is that the avatar's body weight can be realistically changed to a desired numeric reference value. For this purpose, mainly the body mass index calculated as BMI = Body Weight in kg/(Body Height in m)^2 (World Health Organization, 2000) is used. One example is the work of Thaler et al. (2018a), who trained a statistical model to apply realistic BMI-based body weight modification to their generated personalized, photorealistic avatars. But also other factors like muscle mass could be included in such models (Maalin et al., 2020). However, while picture and video-retouching methods tend to focus on facial features, the statistical models of weight gain/loss of avatars in VR are usually trained on the whole body (Piryankova et al., 2014a) or neglect the head region completely (Maalin et al., 2020). For our system, we also learned a statistical model of weight gain/loss for the head region but kept small parts of the face region fixed to preserve the identity of the users when applying the body weight modification.

Besides the shape of the used avatar, application or system-related properties also might alter how we perceive the avatar, and particularly its body weight, in VR. Wolf et al. (2020) presented an overview of potentially influencing factors, noting that while the used display or the observation perspective might unintentionally alter body weight perception (Wolf et al., 2022b), especially the personalization and embodiment of avatars hold potential for application in body image interventions. For example, Thaler et al. (2018a) found that the estimator's BMI influences body weight estimations of a realistic and modulatable avatar, but only when the avatar's shape and texture matched the estimator's appearance. This comes along with a recent review by Horne et al. (2020), who identified the personalization of avatars as an important factor when using avatars. For embodiment, Wolf et al. (2021) recently found, for example, that females' own BMI influences body weight estimations of a generic avatar only when embodying it.

2.2 User experience of a VR-based body image intervention

In the design process of a VR application, it is of utter importance to test the system's user experience (UX). UX refers to the sum of all perceptions and reactions of a user to the interaction with an interface before, during, and after its use (International Organization for Standardization, 2019). It combines a variety of hedonic qualities, such as the joy of the user during an experience, and pragmatic qualities, such as the efficiency of interactions. Concerning the UX evaluation of VR systems, it is suggested to include the assessment of further VR-specific variables (Tcha-Tokey et al., 2016; Wienrich and Gramlich, 2020), namely simulation sickness (Kennedy et al., 1993), the feeling of presence (Slater, 2009), and the feeling of embodiment (Kilteni et al., 2012). Concerning avatar-based body image interventions, particularly the user's feeling of embodiment towards their avatar is of interest (Turbyne et al., 2021). It can be evoked by visuomotor congruence, for example, when the user sees the avatar moving like their real body (Slater et al., 2009, 2010) and is divided into the feeling of being inside (self-location), of owning (virtual body ownership), and of controlling (agency) an avatar (Kilteni et al., 2012).

In addition to a system's classical UX evaluation, it is important to embed the development into an iterative design process. This typically involves understanding and establishing the context of use, defining the requirements for use, developing prototypes, and an iterative evaluation. Wienrich and Gramlich (2020) recently presented the *appRaiseVR* framework for UX evaluation in VR, which adapts the general process of UX design to the context of VR. In their VR-adapted design cycle, they include four steps: 1) defining the setting of the experience, including the details of the system, the planned usage context, and the target user group; 2) defining the level of evaluation, including either an evaluation of the system itself, the task, the narrative, the effect on the user, or the relation between different users; 3) rating the plausibility of the experience, namely its realism, its virtual and physical components; and 4) selecting the time of measure, whether evaluating the expectancy towards a system, the immediate reaction within the experience a post-experience evaluation or follow-up assessments.

Considering this framework, our research evaluates a highly immersive VR system, including a realistic environment and photorealistic, modulatable avatars (1, 3). The design aims at a realistic, clinical setting with a target group dealing with obesity and a disturbed body image (1). Based on our target group, our evaluation focuses on security, physical comfort, and accessibility of our system, next to VR-specific UX and usability of different interaction tasks and the plausibility of avatar modifications (2), which we test during and after the experience (4).

In the context of our application, we further define the effects on body weight perception and physical body awareness during the use as essential parts of the users' experience. For example, Riva et al. (2019) stated that embodiment could potentially help update the misperception of body dimensions by experiencing the ownership over a differently shaped or sized avatar. This goes along with a recent review by Turbyne et al. (2021), summarizing that participants' body image conformed to a modified virtual body size when participants felt embodied in it. VR further interferes with the user's physical body awareness. Filippetti and Tsakiris (2017) showed an increase in body awareness when embodying an avatar for individuals with initially low body awareness. Döllinger et al. (2022) revealed that especially the feeling of body ownership towards a personalized avatar is positively related to body awareness. However, there is no research on body awareness in a VR-based body image treatment task.

2.3 User interaction for body weight modification

Most VR applications for body image interventions aim for enhanced mirror confrontation. They surpass real mirror confrontation by modifying the mirror image or the shown avatars into different body shapes. In our system, we want to go one step further and allow users to adjust the shape of their avatar interactively. Our idea is to give users the opportunity to actively engage in analyzing their body image and develop a novel feeling for their own body. Object manipulation in VR has been widely researched and can serve as a reference in the development of body weight modification interaction methods. For example, LaViola et al. (2017) presented a set of design guidelines for different types of object manipulation, including object scaling by virtual buttons or other control elements, the inclusion of physical interfaces as provided on most VR controllers, or the design of gesture-based object manipulation. Furthermore, Williams et al. (2020) and Wu et al. (2019) investigated the preference of users towards different gestures in object manipulation, and both proposed using two-handed gestures (e.g., moving the hands apart or bringing them together) for size modification of large objects.

2.4 Summary and outline

VR in general, and the embodiment of modulatable avatars in specific, hold great potential to innovate interventions for body image disturbances. The introduced research shows that there exist promising developments toward avatar-based interventions for body image disturbances. However, no work to date undertakes a comprehensive VR-specific UX investigation of such an intervention system.

Our current work within the interdisciplinary research project ViTraS (Döllinger et al., 2019) addresses this research gap and aims toward a novel approach for supporting body image therapy. We present a high-fidelity prototype of a body image therapy support system that allows users to embody their rapidly generated personalized, photorealistic avatar within a carefully designed virtual environment. Our system allows users to dynamically alter their body weight while being embodied in VR using three different interaction methods (joystick, gestures, and virtual objects). We focus on a user experience evaluation with normal-weight participants performed within our first design cycle. In a comprehensive mixed-methods evaluation, we assessed 1) the body scan experience during the avatar generation process, 2) the general, VR-specific UX of the exposure and different modification methods, and 3) their impact on body image-related UX, including body awareness and body weight perception. To sum up our results, we derive a set of guidelines for the design and implementation of future VR systems supporting body image interventions.

3 System description

The technical implementation of our system is realized using the game engine Unity version 2019.4.15f1 LTS (Unity Technologies, 2019). As VR HMD, we use a Valve Index (Valve Corporation, 2020a), providing the user a resolution of 1440 × 1600 pixels per eye with a total field of view of 120° running at a refresh rate of 90 Hz. For motion tracking, we use the two handheld Valve Index controllers, one HTC Vive Tracker 3.0 positioned on a belt at the lower spine, and two HTC Vive Tracker 3.0 on each foot fixed by a velcro strap. The tracking area was set up using four SteamVR Base Stations 2.0. All VR hardware is integrated using SteamVR in version 1.16.10 (Valve Corporation, 2020b) and its corresponding Unity plugin in version 2.7.3.[1] In our evaluation, the system was driven by a high-end PC composed of an Intel Core i7-9700K, an Nvidia RTX2080 Super, and 32 GB RAM running Windows 10. To ensure that users always received a fluent VR experience and to preclude a possible cause of simulator sickness, we measured the motion-to-photon latency of our system by frame-counting (He et al., 2000; Stauffert et al., 2021). For this purpose, the video output was split into two signals using an Aten VanCryst VS192 display

1 https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647.

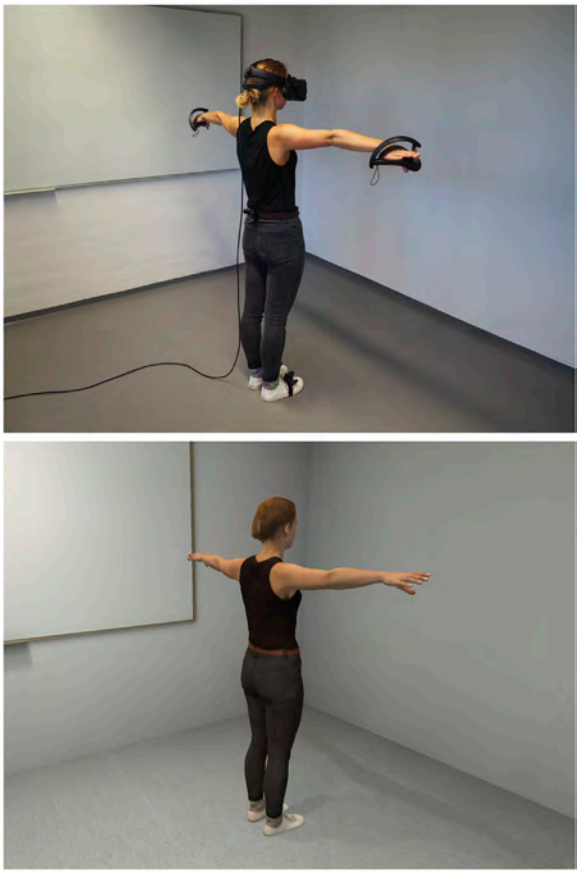

FIGURE 1
The figure depicts a comparison between the real environment where the experiment took place (left) and the replicated virtual environment used for preparation (right). Both environments contain a user, respectively the avatar, performing the embodiment calibration.

port splitter. One signal still led to the HMD, the other to an ASUS ROG SWIFT PG43UQ low-latency gaming monitor. A high-speed camera of an iPhone 8 recorded the user's motions and the corresponding reactions on the monitor screen at 240 fps. The motion-to-photon latency for the HMD matched the refresh rate of the used Valve Index closely, as it averaged 14.4 ms (*SD* = 2.8 ms). The motion-to-photon latency for the body movements was considered low enough to provide a high feeling of agency towards the avatar (Waltemate et al., 2016), as it averaged 40.9 ms (*SD* = 5.4 ms).

3.1 Virtual environments

We realized two virtual environments. The first environment replicates the real environment, in which the user was located physically during our evaluation, and which is automatically calibrated accurately to overlay the physical environment spatially (see Figure 1). Here, all preparatory steps required for exposure are performed and tested (e.g., ground calibration, vision test, equipment adjustments, embodiment calibration). For spatial calibration, we use a customized implementation of the Kabsch algorithm[2] (Müller et al., 2016), based on the positions of the SteamVR base stations in real and virtual environments. Additionally, the virtual ground height is calibrated by briefly placing the controller onto the physical ground.

The second environment is originally based on an asset taken from the Unity Asset Store[3] that was modified to match our requirements. This exposition environment is inspired by a typical office of a psychotherapist with a desk and chairs and an exposure area in which the mirror exposure takes place (see Figure 2). The exposure area includes a virtual mirror allowing for an allocentric observation of the embodied avatar. We aimed for a realistic and coherent virtual environment to enhance the overall plausibility of the exposure (Slater, 2009; Latoschik and Wienrich, 2022).

3.2 Generation and animation of personalized avatars

In our system, the user embodies a personalized avatar from an egocentric perspective while the avatar is animated according to the user's body movements in real-time. The following sections describe the generation of the avatars as well as the animation system.

3.2.1 Generation process

The generation of the avatars closely follows the method of Achenbach et al. (2017). First, the subject is scanned with a custom-made photogrammetry rig consisting of 94 DSLR cameras, where four studio lights equipped with diffuser balls ensure uniform illumination (Bartl et al., 2021). Instead of employing a separate face scanner like Achenbach et al. (2017) did, ten of the 94 DSLR cameras are zoomed in on the subject's face to capture more detail in this region. The images taken by the cameras are then automatically processed with the commercial photogrammetry software Agisoft Metashape (Agisoft, 2021), resulting in a dense point cloud of the subject. We manually select 23 landmarks on the point cloud in order to guide the subsequent template fitting process. The counterparts of these landmarks are pre-selected on the

2 https://github.com/zalo/MathUtilities/#kabsch.

3 https://assetstore.unity.com/packages/3d/props/interior/manager-office-interior-107709.

FIGURE 2
The images show a participant's personalized avatar standing in front of a mirror within the virtual exposition environment of our concept prototype with a reduced (left), normal (center), or increased (right) body weight.

template model, which comes from the Autodesk Character Generator (Autodesk, 2014) and consists of $N \approx 21k$ vertices, an animation skeleton with skinning weights, facial blendshapes, as well as auxiliary meshes for eyes and teeth. Achenbach et al. (2017) enhance the template with a statistical model of human shape variation. This statistical, animatable human template model is then fitted to the point cloud by optimizing for alignment, pose, and shape by employing non-rigid ICP (Bouaziz et al., 2014). This optimization of the model parameters defines the initial registration of the template, which is then further refined by allowing fine-scale deformation of the vertices to match the scanner data more closely. For more details, we refer to Achenbach et al. (2017).

3.2.2 Animation process

For avatar animation, the participants' movements are continuously captured using the SteamVR motion tracking devices. The tracking solution provides for our work a sufficiently solid and rapid infrared-based tracking solution for the crucial body parts required for animation without aligning different tracking spaces (Niehorster et al., 2017). To calibrate the tracking devices to the user's associated body parts and capture the user's body height, arm length, and current limb orientations, we use a custom-written calibration script that requires the user to stand in T-pose for a short moment (see Figure 1). The calibrated tracking targets of the head, left hand, right hand, pelvis, left foot, and right foot were then used to drive an Inverse Kinematics (IK) (Aristidou et al., 2018) approach realized by the Unity plugin FinalIK version 2.0.[4] FinalIK's integrated VRIK solver continuously calculates the user's body pose according to the provided tracking targets. The tracking pose is automatically adjusted to the determined body height and arm length in order to match the user's body. In the next step, the tracking pose is continuously retargeted to the imported personalized avatar. Potentially occurring inaccuracy in the alignment of the pose or the end-effectors can be compensated by a post-retargeting IK-supported pose optimization step. This leads to high positional conformity between the participant's body and the embodied avatar and avoids sliding feet due to the retargeting process.

4 https://assetstore.unity.com/packages/tools/animation/final-ik-14290.

3.3 Body weight modification of avatars

Our system allows the user to modify their body weight during runtime dynamically. The statistical model of weight gain/loss and the implemented user interaction methods are described in the following.

3.3.1 Data-driven body weight modification

To build a statistical model of body weight modification, we follow the approach of Piryankova et al. (2014a), who first create a statistical model of body shape using Principal Component Analysis (PCA) and then estimate a linear function from anthropometric measurements to PCA coefficients. For computing the statistical model of human body shape, we use the template fitting process described above to fit our template model to the European subset of the CAESAR scan database (Robinette et al., 2002). It consists of $M = 1700$ 3D scans, each annotated with anthropometric measurements such as weight, height, arm span, inseam, waist width, etc. After bringing the scans into dense correspondence via template fitting, we are left with M pose-normalized meshes consisting of N vertices each. Our approach for data-driven weight gain/loss simulation differs from the method of Piryankova et al. (2014a) in the following ways: 1) Instead of encoding body shape as a 3×3 deformation matrix per mesh face (Anguelov et al., 2005), we encode body

FIGURE 3
The figure illustrates our approach of facial weight gain simulation. When modifying the weight of an avatar (left), part of the face region (highlighted in red) is fixed (center left). The modified vertices are stitched to the face region in a seamless manner using differential coordinates (Sorkine, 2005) (center right). Not keeping these vertices fixed would require recalculating the position of all auxiliary meshes such as eyes and teeth due to the undesired change in facial proportions for nose, mouth and eyes stemming from changing the parameters of the underlying face model (right). For the right image, eyes are copied from the unmodified avatar in order to better highlight the change in shape and position.

shape directly via vertex positions. 2) Modelling weight gain/loss as a change in parameters of a statistical parametric shape model (Piryankova et al., 2014a; Xiao et al., 2020) changes face identity during weight modification due to the fact that the learnt direction of change is not subject-specific. This leads to effects such as changing the shape of the eye socket, the pupillary distance or other unrealistic changes in face proportions. To mitigate these effects, we keep vertices in the face region fixed while deforming the rest of the mesh in order to preserve the identity of the participants.

To this end, we define a set $\mathcal{S}$ with cardinality V containing all vertices outside of the face region (see Figure 3) as well as a selector matrix $\mathbf{S} \in \mathbb{R}^{3V\times 3N}$ which extracts all coordinates belonging to vertices in $\mathcal{S}$. Let $\mathbf{x}_j = (\mathbf{p}_1^T, \ldots, \mathbf{p}_N^T)^T \in \mathbb{R}^{3N}$ be the vector containing the stacked vertex positions of the jth training mesh and $\bar{\mathbf{x}} = \frac{1}{M}\sum_j \mathbf{x}_j \in \mathbb{R}^{3N}$ be the corresponding mean. Performing PCA on the data matrix $\mathbf{X} = (\mathbf{S}\mathbf{x}_1 - \mathbf{S}\bar{\mathbf{x}}, \ldots, \mathbf{S}\mathbf{x}_M - \mathbf{S}\bar{\mathbf{x}}) \in \mathbb{R}^{3V\times M}$ and taking the first $k = 30$ components then yields the PCA matrix $\mathbf{P} \in \mathbb{R}^{3V\times k}$. Let $\mathbf{W} = (\mathbf{w}_1, \ldots, \mathbf{w}_M) \in \mathbb{R}^{k\times M}$ contain the PCA coefficients w_j of the M training meshes, computed by $\mathbf{w}_j = \mathbf{P}^T(\mathbf{S}\mathbf{x}_j - \mathbf{S}\bar{\mathbf{x}})$. If we denote by $\mathbf{D} \in \mathbb{R}^{M\times 4}$ the matrix containing the anthropometric measurements weight, height, armspan and inseam of the jth subject in its jth row, we can then compute a linear mapping from anthropometric measurements D to PCA coefficients W by solving the linear system of equations $(\mathbf{D} \mid \mathbf{1})\mathbf{C} = \mathbf{W}^T$ in a least-squares sense via normal equations.

New vertex positions for a subject with initial vertex positions x and a desired change in anthropometric measurements $\Delta\mathbf{d} \in \mathbb{R}^5$ can then be calculated via $\tilde{\mathbf{x}} = \mathbf{S}\mathbf{x} + \mathbf{P}(\mathbf{C}^T\Delta\mathbf{d})$, i.e., by first projecting the desired change in measurements into PCA space via the learned linear function and then into vertex position space via the PCA matrix. However, this only updates vertices in $\mathcal{S}$. In order to seamlessly stitch the new vertex positions to the unmodified face region, we compute the Laplacian coordinates (discretized through cotangent weights and Voronoi areas (Botsch et al., 2010)) of the resulting mesh and then use surface reconstruction from differential coordinates (Sorkine, 2005). For the vertices of the face region and its 1-ring neighborhood, the Laplacian is computed based on the unmodified vertex positions x, while for the rest of the vertices, the Laplacian is computed based on the modified vertex positions $\tilde{\mathbf{x}}$. Since the position of vertices of the face region is known and should not change, we treat the position of these vertices as *hard* instead of *soft* constraints as discussed by Botsch and Sorkine (2008). Setting $\Delta\mathbf{d} = (\Delta w, 0, 0, 0, 0)^T$ then allows modifying the user's weight while keeping the other anthropometric measurements fixed. Keeping the face region fixed 1) preserves the identity of the user for high values of Δw and 2) avoids having to recalculate the position of auxiliary meshes of the avatar such as eyes and teeth (Figure 3). Results of the described body weight modification method are shown in Figure 4.

3.3.2 Interaction methods

To allow users to modify the avatars' body weight as quickly, easily, and precisely as possible, we compare in our evaluation three implemented interaction methods regarding their usability. Since interaction methods for human body weight modification have not yet been explored, we considered the guidelines for object modification presented by LaViola et al. (2017). Figure 5 gives a short overview of the body weight modification methods. After a pilot test of body weight modifications with multiple generated virtual humans, we restricted the body weight modification for all interaction methods to a range of ±35% of the user's body weight to

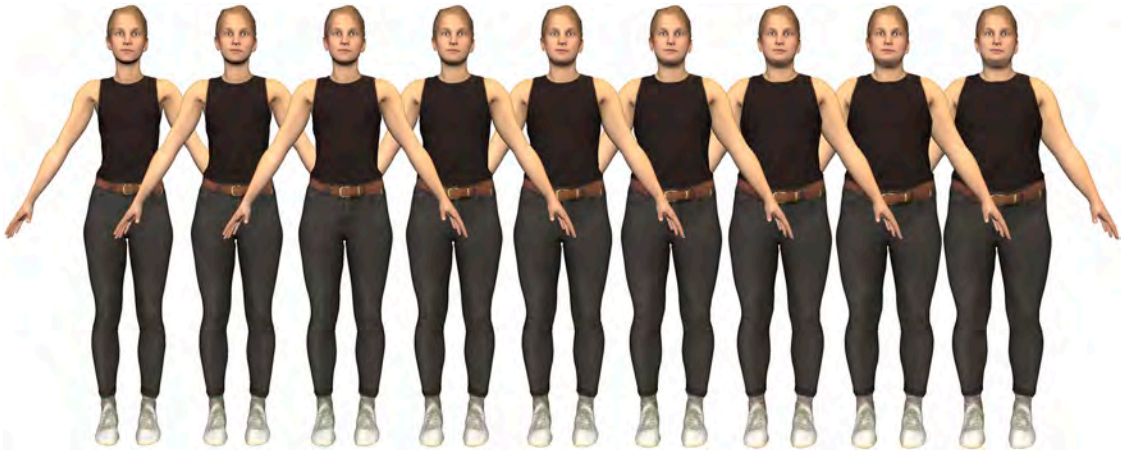

FIGURE 4
The figure shows a generated female avatar (BMI = 19.8) with modified body weight corresponding to a BMI range of 16–32 in two-point increments.

avoid unrealistic, possibly unsettling shape deformation. To avoid providing any hidden cues, we have extended the possible modification range compared to the used modification range of our passive estimation task. The constants given in the formulas for calculating the velocity of body weight change were determined empirically in a further pilot test.

3.3.2.1 Body weight modification via controller movement gestures

To modify the avatar's body weight via gestures (see Figure 5, left), users have to press the trigger button on each controller simultaneously. Moving the controllers away from each other then increases the body weight, while moving them towards each other decreases it. The faster the controllers are moved, the faster the body weight changes. When active, the body weight changes by the velocity v in kg/s, determined by the relative distance change between the controllers r in m/s, and calculated as $v = 3.5r^2 + 15r$.

3.3.2.2 Body weight modification via joystick movement

To modify the avatar's body weight via joystick (see Figure 5, center), users have to tilt the joystick of either the left or the right controller. Selecting joystick for an initial modification leads to a deactivation of the other joystick for the remaining interaction. Tilting the joystick to the left decreases the body weight, tilting it to the right increases it. The stronger the joystick is tilted, the faster the body weight changes. When enabled, the body weight changes by the velocity v in kg/s, determined by the normalized tilt t of the joystick and calculated as $v = 10t^2 + 5$.

3.3.2.3 Body weight modification via controller movement towards objects

To modify the avatar's body weight via objects (see Figure 5, right), users have to touch either a virtual "plus" or a virtual "minus" object within the virtual environment. As long as an object is touched, the body weight increases or

FIGURE 5
The figure sketches the three body weight modification methods we used for our evaluation: Gestures (left), Joystick (center), and Objects (right).

10.3389/frvir.2022.935449

decreases. The longer the object is touched, the faster the body weight changes. When active, the body weight modification velocity v in kg/s increases quadratically over a normalized contact duration d of 1.5 s in a normalized range r between 3 kg/s and 15 kg/s.

4 Evaluation

We tested our first system prototype in a structured UX evaluation based on multiple relevant qualitative questions and quantitative measures concerning the users' scan and VR exposure experience as well as their body image. The following sections contain a detailed explanation of the evaluation process.

4.1 Ethics

Since our technical system was developed with the aim of being tested on potential patients in a clinically relevant context as part of a later feasibility study, particular attention has already been paid to ethical aspects during the here reported development and evaluation of our system. As part of a conservative development and evaluation strategy, we decided to work with a relatively small sample of healthy participants in this initial formative evaluation. The system, as well as the evaluation, was designed in consultation with our clinical partners within the context of our interdisciplinary research project ViTraS (Döllinger et al., 2019). A detailed ethics proposal following the Declaration of Helsinki was submitted to the ethics committee of the Human-Computer-Media Institute of the University of Würzburg and found to be ethically unobjectionable. Free professional help services provided by the Anorexia Nervosa and Associated Disorders (ANAD)[5] organization were explicitly highlighted during the acquisition and evaluation process.

4.2 Participants

A total of 12 students (8 female, 4 male) of the University of Würzburg participated in our evaluation and received course credit in return. Before the evaluation, we defined four exclusion criteria queried by self-disclosure: Participants had to have 1) normal or corrected to normal vision and hearing, 2) at least 10 years of experience with the German language, 3) not suffered from any kind of mental or psychosomatic disease, or from body weight disorders, and 4) no known sensitivity to simulator sickness. None of the participants matched any exclusion criteria. The participants were aged between 20 and 25 (M = 22.0, SD = 1.48), had a BMI between 17.85 and 32.85 (M = 22.72, SD = 3.98), and had mostly very little VR experience. Nine out of the twelve participants claimed to know their current body weight. The mean deviation of the indication of their body weight compared to that measured by the experimenter was 0.29 kg (SD = 1.57).

5 https://www.anad.de/.

4.3 Design

The evaluation of our system included qualitative and quantitative measures regarding 1) the body scan experience, 2) the UX of the VR exposure and the different modification methods used, and 3) their impact on the body image-related measures body awareness and body weight estimation. To compare our three modification methods (see Figure 5), participants performed for each modification method a set of active modification tasks (AMTs) in a counterbalanced order using a 1 × 3 within-subjects design. For comparing the novel AMT with the more traditional passive estimation task (PET), the participants performed a PET each before and after the AMTs (see Figure 6, right). All tasks and the timing of the measures will be further explained in Section 4.5.

4.4 Measures

4.4.1 Body scan experience

We conducted a semi-structured interview to evaluate the body scan experience. It included questions concerning the participants' expectations, their physical and psychological comfort and/or discomfort during the body scan and the assessment of their body measures, and about the clarity and transparency of the process. A full version of the questions can be found in the supplementary material of this work.

4.4.2 VR experience

Regarding the VR experience, we included a variety of VR-specific and task-specific UX measures to get a holistic view of the system's overall UX. We used a combination of qualitative and quantitative measures, in virtuo ratings, and pre- and post-questionnaires for the VR UX evaluation.

4.4.2.1 Interview

We conducted another instead of a semi-structured interview with focus on the VR experience. It included questions concerning the participants' expectations and feelings towards the avatar, their favored body weight modification method and the perceived difficulty of the body weight estimation in general, their intensity of body awareness, and their affect towards their body. A full version of the questions can be found in the supplementary material of this work.

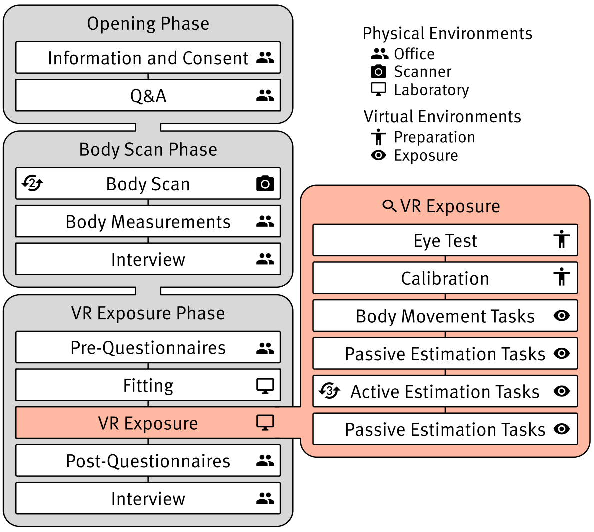

FIGURE 6
The figure provides an overview of the evaluation process as whole (left) and a detailed overview of the VR exposure (right). The icons on the right side of each step show in which physical or virtual environment the step was conducted. The icons on the left side indicate when steps were repeated.

4.4.2.2 Presence

We measured the participants' feeling of presence using the Igroup Presence Questionaire (IPQ) (Schubert et al., 2001). It captures presence through 14 questions, each rated on a scale from 0 to 6 (*6 = highest presence*). The items are divided into four different dimensions: general presence, spatial presence, involvement, and realism. The questionnaire was provided directly after the VR exposure to capture presence as accurately as possible.

4.4.2.3 Embodiment

As suggested by prior work, we divided the measurements for the feeling of embodiment into VBO and agency (Kilteni et al., 2012). Following Waltemate et al. (2018) and Kalckert and Ehrsson (2012), we presented one embodiment question for each dimension on a scale from 0 to 10 (*10 = highest*). Both questions based on items of the Virtual Embodiment Questionnaire (VEQ) of Roth and Latoschik (2020). To investigate possible differences in the feeling of embodiment caused by our interaction methods, the questions were provided multiple times during exposure.

4.4.2.4 Simulator sickness

To test our system prototype regarding simulator sickness caused by latency jitter or other sources (Stauffert et al., 2018; Stauffert et al., 2020), we included the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993; Bimberg et al., 2020) before and after the VR exposure. It captures the appearance and intensity of 16 different simulator sickness associated symptoms on 4-point Likert scales. The total score of the questionnaire ranges from 0 to 235.62 (*235.62 = strongest*). An increase in the score by 20 between a pre- and post-measurement indicates the occurrence of simulator sickness (Stanney et al., 1997).

4.4.2.5 Avatar perception

For measuring the affect towards the avatar, we used the revised version of the Uncanny Valley Index (UVI) (Ho and MacDorman, 2017), including its four sub-dimensions: humanness, eeriness, spine-tingling, and attractiveness. Each dimension is captured by four to five items ranging from 1 to 7 (*7 = highest*).

4.4.2.6 Workload

We measured workload to 1) determine the perceived effort during the calibration of the system and to 2) determine the perceived difficulty when modifying the avatar's body weight with our modification methods. To capture workload fast and efficiently during VR, we used a single item scale ranging from 0 to 220 (220 = highest) called SEA scale (Eilers et al., 1986), a German version of the Rating Scale Mental Effort (Zijlstra, 1993; Arnold, 1999).

4.4.2.7 Preference rankings

Participants were asked to order the three body weight modification methods concerning their workload, perceived body weight estimation difficulty, vividness, contentment, and overall preference. Ranking scores were then calculated using weighted scores with reversed weights. A weighting of 4 was used for the highest rank, a weighting of 3 for the second highest, and so on. The overall rankings were summed up and averaged over the number of ratings. A high scores states high workload, difficulty, vividness, contentment, and overall preference.

4.4.2.8 Calibration and modification time

To measure the efficiency of the avatar calibration and the interactions methods, we captured the average time needed from the beginning of calibration or modification until the end. Calibration time included potential amendments of the avatar skeleton and re-calibrations. A lower time states a higher efficiency.

4.4.3 Body image

4.4.3.1 Body awareness

Similar to VBO, agency, and workload, we included (virtual) body awareness (VBA) as a one-item scale from 0 to 10 (*10 = highest VBA*) assessed at multiple times during exposure. The item was derived from the State Mindfulness Scale (SMS) (Tanay and Bernstein, 2013).

4.4.3.2 Passive body weight estimation (PET)

The PET was adapted from prior work (Wolf et al., 2020, 2021, 2022a) and used to capture the participants' ability to numerically estimate the avatars' body weight based on a provided body shape. We repeatedly modified the body weight of the embodied avatar within a range of ±20% incremented in 5% intervals in a counterbalanced manner resulting in $n = 9$ modifications. To not provide any hints on the modification direction, the HMD was blacked-out during the modification. For each modification, the participants had to estimate the avatar's body weight in kg, which we used to calculate the misestimation M. It is based on the estimated body weight e and the presented body weight of the avatar p as $M = \frac{e-p}{p}$. A negative value states an underestimation, a positive value an overestimation. Additionally, we calculated 1) the average misestimation $\bar{M} = \frac{1}{n}\sum_{k=1}^{n} M_k$ and 2) the absolute average percentage of misestimation as $\bar{A} = \frac{1}{n}\sum_{k=1}^{n} |M_k|$.

4.4.3.3 Active body weight estimation (AMT)

The AMT was inspired by related work (Piryankova et al., 2014a; Thaler et al., 2018a,b) and used to capture the participants' ability to modify the avatar's body weight to match a requested numeric value. We also used it to analyze whether a certain interaction method for body weight modification influenced the participant's ability to judge the avatars' body weight. Participants had to modify the avatar's body weight by using one of our modification interaction methods until they thought it matched a presented numeric target weight in kg. The task was repeated for a target weight range of ±20% of the actual avatar's body weight incremented in 5% intervals in a counterbalanced manner resulting in $n = 9$ modifications. For each modification, we calculated the misestimation M based on the modified body weight m and the target body weight t as $M = \frac{t-m}{t}$. A negative value states an underestimation, a positive value an overestimation. Additionally, we calculated $\bar{M}$ and $\bar{A}$ as for the PET.

4.5 Procedure

The entire evaluation took place in three adjacent rooms (office, body scanner, laboratory) of the University of Würzburg and averaged 117 min. The procedure is illustrated in Figure 6.

4.5.1 Opening phase

First, participants were informed about the local COVID-19 regulations, received information about the experiment and the body scans, gave their consent, and generated two personal pseudonymization codes used to store the experimental data and the generated avatars separately. Then, the main experimenter answered potential questions and measured the participant's body height without shoes as required for the body scan.

4.5.2 Body scan phase

An auxiliary experimenter performed the body scan in normal clothes without any accessories. Afterwards, the main experimenter measured the interpupillary distance (IPD), body weight, and the participants' waist and hip circumference, and conducted the interview about the scan process. The duration of the interview averaged 4 min. All interviews were recorded by a Tascam DR-05 voice recorder.

4.5.3 VR exposure phase

Prior to the VR exposure, participants answered demographic questions and the SSQ as pre-questionnaires on a dedicated questionnaire computer. Then, an auxiliary experimenter demonstrated the participants how to fit the equipment, adjusted the HMD's IPD, and controlled that all equipment was correctly attached. After finishing the fitting, a pre-programmed experimental procedure was started, and participants were transferred to the preparation environment. For all virtual transitions during the VR exposure, the display was blacked-out for a short moment. All instructions were displayed on an instruction panel and additionally played as pre-recorded voice instructions. As the first preparation step, the participants had to undergo a short reading test to ensure the view was sufficient. Then, they performed the embodiment calibration in T-pose and judged its workload. During the whole VR exposure, participants had to answer questions and measurements verbally. Although interaction between the experimenter and the user may cause small breaks in presence (Putze et al., 2020), we considered this approach as part of the evaluation, since interaction between patient and the rapist would also likely occur in clinical settings and advanced in virtuo interaction to answer questionnaires might be difficult for novice users.

After the preparation finished, participants were transferred to the exposition environment. There, they performed five movement tasks in front of a virtual mirror while being instructed to alternatingly look at the mirror and directly on their body to induce the feeling of embodiment. Movement tasks were adapted from related work (Wolf et al., 2020) and had to be performed for 20 s. The first PET followed. Participants estimated the modified body weight of their avatar nine times. Between the estimations, the display was blacked-out briefly to cover the weight changes. In the next phase, participants conducted AMTs nine times for each body weight modification method in a counterbalanced manner. For all body weight estimation tasks, no feedback regarding the estimation error was provided to the participants. The second PET concluded the phase. After each AMT (see Figure 6), participants were asked to judge workload, agency, VBO, and

VBA in virtuo. The whole VR exposure took 36 min on average. After the VR exposure, participants answered IPQ, SSQ, UVI, and UX questions again on the dedicated questionnaire computer.

4.5.4 Closing and debriefing phase

The questionnaires were followed by the second interview about the VR exposure that lasted on average 11 min. At the end of the session, the main experimenter thanked the participants and granted them credits for their participation. As part of the debriefing process after the session, the interviews were first transcribed and then two researchers summarized and clustered the answers into categories.

5 Results

In this section, we report the results of our evaluation separated into 1) the body scan experience, 2) the UX of the VR exposure including the different modification methods, and 3) their impact on body image-related measures. The statistical analysis of our results was partially performed using the software R for statistical computing (R Core Team, 2020) and partially using SPSS version 26.0.0.0 (IBM, 2020). All tests were performed against an α of .05.

5.1 Body scan experience

5.1.1 Feedback on the body scanning process

When asked whether the body scan procedure matched their idea of a body scan, four participants expected a different amount or arrangement of cameras, three participants expected a different scan process (e.g., one camera moving around the body, a laser measuring the body shape, or cameras only in the front), and one participant claimed to have no previous expectations on the body scan process. The other participants stated they already knew the body scan procedure from former experiments and did not remember expectations.

Most of the participants perceived the scan process as simple and clear. Only one participant stated not knowing what was happening between two scans. The experience during the scan process differed from "straightforward" and "easy" (n = 4) over "interesting" or "cool" (n = 4) to being "something to getting used to" or making one "feel observed" (n = 4).

All participants stated positively they would do a body scan again. While most of them did not have suggestions for improvement (n = 8). One suggested that the experimenter should be visible during the whole scan process to increase a feeling of safety. Others pointed out that a reduced number of cameras would ease the feeling of being watched and that the stiff posture during the scan felt kind of uneasy after some time.

5.1.2 Feedback on the body measurements

When evaluating the assessment of body measures, most participants claimed to perceive it as neutral or similar to being measured during a doctor's appointment (n = 8). Some others pointed out they would not expect it in a "normal" lab study but did not perceive it as awkward (n = 3). One participant stated to perceive the measuring of their weight as very private and therefore uncomfortable.

5.2 VR experience

Since there was no comparison condition to the overall quantitative scores of the VR experience, we report the data, which were mainly collected on validated and comparable scales, descriptively. For measures captured multiple times during the experience, we calculated the mean value of all data points. The descriptive results of the VR exposure experience are summarized in Table 1.

To evaluate the possible occurrence of simulator sickness, we compared SSQ pre- and post-measurements. The observed increase in SSQ scores of 16.21 was below the indication threshold for simulator sickness of 20 points (Stanney et al., 1997), implying a safe use of the application with respect to potential simulator sickness-related impacts. Further, a two-tailed Wilcoxon signed-rank test revealed that the median ranks did not differ significantly between measurements, Z = 1.14, p = .254.

5.2.1 Feedback on embodiment and avatar perception

When asked about their feelings towards their personalized avatar, two participants used "neutral" or "okay" to describe their experience, and another four participants described it as "cool", "interesting", or "pleasant". The remaining six participants described the experience as less positive, using words like "strange" and "irritating". While one of the former emphasized the quality of the embodiment compared to other studies, three of the latter criticized the embodiment, especially concerning the lack of facial expression, eye movements and hand gestures. One pointed out that their "hands hold these controllers but the avatar does not". The participants who found the experience rather irritating emphasized a lack of similarity in their avatar's appearance.

The question of whether the avatar's appearance met the participants' expectations also received mixed responses. While one participant found it overall disproportional, six participants stated that the look of their avatar rather met their expectations. The remaining participants indicated that although the avatar's

TABLE 1 The table shows the descriptive values for our captured measurements concerning the VR experience. Detailed information regarding the measurements can be found in Section 4.4.

Measure	Variable	[Range]	*M* (*SD*)
Presence	IPQ General presence	[0–6]	4.58 (0.90)
	IPQ Spatial presence	[0–6]	4.38 (0.95)
	IPQ Involvement	[0–6]	3.75 (0.89)
	IPQ Realism	[0–6]	3.22 (1.2)
Embodiment	VBO score	[0–10]	5.49 (2.33)
	Agency score	[0–10]	7.22 (1.94)
Simulator sickness	Pre-SSQ	[0–235.62]	26.8 (23.7)
	Post-SSQ	[0–235.62]	43.01 (39.21)
Avatar perception	UVI Humanness	[1–7]	4.03 (1.10)
	UVI Eeriness	[1–7]	4.06 (0.95)
	UVI Spine-tingling	[1–7]	3.88 (0.88)
	UVI Attractiveness	[1–7]	4.25 (0.87)
Calibration workload	SEA score	[0–220]	20.83 (16.35)
Calibration time	Time in s		96.79 (50.29)

body looked as expected, they did not associate its face with themselves.

5.2.2 Comparison of the body weight modification methods

For comparing the three AMT conditions (gesture, joystick, and objects), we calculated a one-way repeated-measures ANOVA for each listed measurement (see Table 2) except modification times, where we calculated a Friedman test, and preference rankings, which are presented descriptively only. Test results showed significant differences between conditions only for workload, F (2, 22) = 13.95, p < .001. Two-tailed paired-sample post-hoc t-tests revealed significant differences in the SEA score between body weight modifications with gesture and joystick, t (11) = 2.74, p = .019, gesture and objects, t (11) = 2.8, p = .017, and joystick and objects, t (11) = 4.86, p = .001. Thus, the workload was considered to be highest when modifying body weight via objects and lowest when using the joystick.

5.2.3 Feedback on the body weight modification methods

When asked to explain their preference for an interaction method, most of the participants who preferred joystick (n = 8) stated that it felt most controllable and least complicated. One participant additionally preferred the continuity of joystick-based interaction compared to the necessity of repetition in the gesture-based interaction. The participants who had preferred the gesture-based interaction (n = 4) stated they found it most intuitive, flexible, and direct. They reasoned that controlling the speed of modification by extent and speed of arm movements increased usability. None of the participants preferred modification via the objects.

5.3 Body image

In the following, we present the impact of our VR exposure on the body image-related measures of body awareness and body weight estimation as well as the related qualitative feedback.

5.3.1 Comparison of body awareness between body weight modification methods

We calculated a one-way repeated-measures ANOVA to compare the body awareness (VBA) during the three AMT conditions (gesture, joystick, and objects). As shown in Table 2, VBA ratings differed tendentially between the three AMT conditions, with higher joystick ratings than the other conditions, F (2, 22) = 3.37, p = .053.

5.3.2 Feedback on the intensity of body awareness

Seven participants stated they felt in contact with their physical body during the experience, while the other five stated they had lost contact to their body at least once. The latter stated, for example, they focused mainly on the task and the avatar. Others felt that their bodily awareness “got a bit lost” or that the situation and virtual surroundings made them forget reality, including their real body. On the other hand, three participants who stated being aware of their body during the experiment reasoned the embodiment as a main cause. One of them stated that “once before re-calibration, my avatar’s foot was kind of crooked, that’s when I paid attention to my real body. I made sure my knee was straight”. The other one focused on the avatar weight and claimed that “I was still aware of my body, but it was very strange because I was looking at a different mirror image, and sometimes, I felt much heavier when the weight of the avatar was lower than my actual weight”. Another reason why participants were aware of their bodily sensations was the physical contact with the floor or the proprioception during movements, which reminded them of their presence in the physical room (n = 2).

5.3.3 Feedback on the affect towards the body

Eight of the participants stated that their feelings towards their bodies had changed during the experience. These changes concerned either their general awareness (n = 3), their experienced body size (n = 2), or their satisfaction with their body (n = 3). The two participants stating a change in their experienced body size had either felt thicker or thinner in contrast to their avatar during the experience or felt thinner after the experience. Two of the participants whose bodily satisfaction changed stated an increased body

TABLE 2 The table shows all descriptive values of the measures related to the comparison between our proposed body weight modification methods including *p*-values when calculated. Asterisks indicate significant *p*-values. Post-hoc tests for significant differences can be found in the corresponding text.

Measure	Variable	[Range]	Gestures	Joystick	Objects	*p*
			M **(*SD*)**	***M*** **(*SD*)**	***M*** **(*SD*)**	
Embodiment	VBO	[0–10]	5.75 (2.63)	5.08 (2.68)	5.38 (2.5)	.300
	Agency	[0–10]	7.25 (2.61)	7.16 (2.29)	7.33 (2.02)	.915
Modification time	Time in s		23.19 (2.94)	24.53 (10.37)	27.82 (7.72)	.197
Workload	SEA	[0–220]	41.25 (27.97)	20.75 (13.37)	65.33 (33.06)	< .001*
	Ranking	[1–4]	1.91	2.73	3.45	–
Task Difficulty	Ranking	[1–4]	3	1.81	3.36	–
Vividness	Ranking	[1–4]	3.09	3.09	2.27	–
Contentment	Ranking	[1–4]	3.36	3.45	1.91	–
Overall preference	Ranking	[1–4]	3.27	3.45	2.09	–
Body awareness	VBA	[0–10]	6.58 (1.98)	7.08 (1.93)	6.67 (2.06)	.053

satisfaction or increased motivation to care for their bodily interests. In contrast, one participant reported increased dissatisfaction towards their physical body after the experience.

5.3.4 Feedback on the perception of body weight changes

Concerning the changes in the avatar's body weight, the participants equally rated them as "interesting" (n = 6) or "weird" (n = 6). Two participants especially pointed out that it was interesting to compare the avatar's body shape to their own former body, as they had lost or gained weight in the past. One stated "when I started my studies 5 years ago, I was 20 kg lighter than now, and it was kind of interesting to compare the avatar's look to the memories of my old body shape. It gave me a little perspective on how I want to look". Four of the other participants liked the idea of seeing how they could look if they changed their eating/exercise behavior. Especially the modification towards a lower weight was perceived as threatening by some of the participants (n = 3), as they thought it looked a bit unhealthy. To enhance the modification, two participants suggested more individual and fine-grained possibilities to manipulate only body parts instead of the body as a whole, for example, by including "two fixed points on the virtual body, one in the middle of the body and one at the shoulder area, to adjust the weight in these areas more exactly".

5.3.5 Comparison of body weight estimations between body weight modification methods

For comparing the performance in body weight estimations between the AMT, we calculated a one-way repeated-measures ANOVA for $\bar{M}$-values, the percentage body weight misestimation, and a Friedman test for $\bar{A}$-values, the absolute percentage body weight misestimation. The tests revealed that the three interaction methods did not differ significantly, neither in $\bar{M}$, F (2, 22) = 0.66, p = .529, nor in $\bar{A}$, χ^2 (2) = 0.50, p = .779, as summarized in Table 3.

5.3.6 Comparison of body weight estimations between estimation methods

We compared AMT and PET using two-tailed paired-samples t-tests for $\bar{M}$-values and two-tailed Wilcoxon signed-rank tests for $\bar{A}$-values. For $\bar{M}$, we showed that participants misestimated the body weight significantly less using the PET (M = 1.46, SD = 8.4) than when using the AMT (M = 3.1, SD = 8.4), t (11) = 2.47, p = .031. For $\bar{A}$, the median ranks for PET, Mdn = 6.28, were tendentially lower than the median ranks for AMT, Mdn = 7.85, Z = 1.88, p = .060.

We further analyzed the results of AMT and PET concerning the modification levels (±20% in 5% steps) using linear regression. Our data violated pre-requirements for linear regression in terms of homoskedasticity and normality. Therefore, we calculated each linear regression using parameter estimations with robust standard errors (HC4) as recommended by Hayes and Cai (2007). Figure 7 shows the body weight misestimations M (left) and the absolute body weight misestimations A (right) for PET and AMT in relation to the modification levels.

For M, the results showed a significant regression equation for PET, F (1, 106) = 7.88, p = .006, with a R^2 of 0.069. The prediction followed equation $M = -0.194 \times$ Body Weight Modification in % instead of a simple point. The modification level did significantly impact on body weight misestimations M, t (106) = 5.11, p = .013. For AMT, we found no significant prediction of the modification level on the body weight

TABLE 3 The table summarizes the body weight estimation performance (average misestimation $\bar{M}$ and absolute average of misestimation $\bar{A}$) of the comparison between our proposed modification methods.

	Gestures	Joystick	Objects	*p*
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	
$\bar{M}$ in %	3.44 (9)	3.44 (8.9)	2.41 (8.05)	.529
$\bar{A}$ in %	8.92 (4.58)	8.46 (5.10)	8.36 (3.66)	.780

misestimations *M*, *F* (1, 106) = 3.05, *p* = .084, having a R^2 of 0.028. The found prediction followed equation *M* = −0.120. Body Weight Modification in % + 3.099. In consequence, the modification level did not significantly impact on body weight misestimations *M*, *t* (106) = −3.46, *p* = .094.

For *A*, the results showed a significant regression equation for PET, *F* (1, 106) = 5.27, *p* = .024, with a R^2 of 0.047. The prediction followed equation A = −0.101 × Body Weight Modification in % + 7.743. The modification level did significantly impact on body weight misestimations *A*, *t* (106) = −2.09, *p* = .039. For AMT, we found a significant prediction of the modification level on the body weight misestimations *A*, *F* (1, 106) = 15.7, *p* < .001, with a R^2 of 0.129. The found prediction followed equation *M* = −0.147 × Body Weight Modification in % + 8.585. The modification level did significantly impact on body weight misestimations *A*, *t* (106) = −17.9, *p* < 0.001.

In addition to the linear regressions, we averaged body weight estimations for negative and positive modifications for both measurements to analyze differences between the modification directions. Again, we compared AMT and PET using two-tailed paired-samples t-tests for *M*-values and two-tailed Wilcoxon signed-rank tests for *A*-values. Test results for *M*-values showed that body weight misestimations in PET differed significantly between negative (*M* = 3.96, *SD* = 11.13) and positive (*M* = −1.09, *SD* = 7.44) modifications, *t* (11) = 2.27, *p* = .044, but misestimations in AMT did not differ between negative (*M* = 4.86, *SD* = 10.57) and positive (*M* = 1.38, *SD* = 7.45) modifications, *t* (11) = 1.63, *p* = .131. For *A*-values, we found no significant differences between the median negative ranks, *Mdn* = 7.23, and the median positive ranks, *Mdn* = 5.80, modifications for PET, *Z* = 1.26, *p* = .209, but found significant differences between the median negative ranks, *Mdn* = 9.51, and the median positive ranks, *Mdn* = 5.39, modifications for AMT, *Z* = 2.59, *p* = .010.

5.3.7 Feedback on the body weight estimation difficulty

Regardless of the estimation method, estimating the body weight of the avatar was found to be difficult (*n* = 8). Only three participants stated they found it relatively easy or only medium-difficult to estimate the body weight. The main reason why participants rated the task as difficult was the high number of repetitions (*n* = 2) or a reduced perceptibility of their physical body, both leading to a "loss of perspective". Additionally, one participant stated that the task difficulty depended on the distance of the avatar's weight to their own.

6 Discussion

In the present paper, we introduced a prototype of an interactive VR-based system that aims to support body image interventions based on embodied, modulatable, and personalized avatars in future clinically relevant settings. We evaluated the system regarding 1) the body scan experience, 2) the general UX of the VR exposure including body weight modification interaction methods, and 3) the body-image specific UX of the exposure, namely the impact on body awareness and body weight perception. In the following, we summarize and discuss the results of our evaluation to ultimately derive guidelines supporting the design of systems for body image interventions. The guidelines are based on conclusions of the

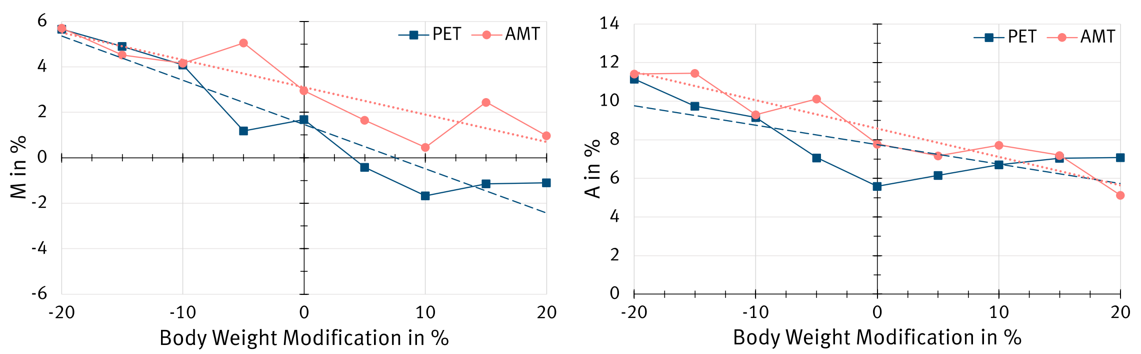

FIGURE 7
The figure shows the body weight misestimations *M* (left) and absolute body weight misestimations *A* (right) in relation to the performed body weight modifications for PET and AMT.

qualitative and quantitative results accomplished by the researchers' observations and participants' comments during the evaluation. While these may overlap with existing best practices or established VR guidelines, we believe it is elementary to summarize them for the given context and to highlight their importance.

6.1 Body scan experience

Overall, the scan process was mainly rated as simple and interesting, although it took place in a separate room with great technical effort. Participants stated a high acceptance and willingness to be scanned again. In addition, the scan and the associated body measurements were seen as something that one would do in a clinical setting, and that does not trigger unpleasant reservations. This assessment strengthens the idea of using body scans in a clinical context.

Nevertheless, two main criticisms of the scanning process were the feelings of being watched and being left alone. The large number of visible cameras mainly caused the first while both can be attributed to the arrangement of the cameras surrounding the person in all directions. Curtains around the scanner also supported the feeling of being left alone during the scan process. In particular for our target group and the intended clinical usage, amendments seem necessary. Options to reduce the negative feelings could be a change in the arrangement of cameras, e.g., opening the space by placing them only on one side or reducing the number of cameras to a minimum as proposed by Wenninger et al. (2020) and supported by the results of Bartl et al. (2021). In addition, we suggest a constant dialogue about and during the process to counteract the feeling of being alone.

Guidelines for Body Scanning

- Users should receive thorough information and instruction in advance about the body scan procedure to provide clarity and transparency.
- Body scans should be performed unobtrusively to protect privacy and avoid the feeling of being watched.
- The number and arrangement of cameras should be planned carefully to avoid the feeling of being watched.
- The number of people involved in the body scan should be minimized to increase privacy, and personal contact should be maximized to increase safety.
- Body-related measurements should be performed professionally while maintaining privacy.

6.2 User experience of VR experience

The feedback regarding preparation and calibration was consistently positive, confirming the decision for our approach. This is empirically supported by the low measured calibration times requiring only a short time holding T-pose, and the low workload ratings during the calibration process. Nevertheless, there are further possibilities to reduce the effort for calibration and invasiveness, for example, by using completely markerless body tracking solutions (Wolf et al., 2022a).

Regarding VR-specific measures, participants rated their perceived feeling of presence on an acceptable level (Buttussi and Chittaro, 2018; Wolf et al., 2020), with lower ratings on involvement and realism. A reason for the lower observed involvement score could be the constant interaction with the experimenter during the tasks (e.g., confirming body weight estimations, rating experiences). Possible implausible content (e.g., body weight modification by interaction) could have impacted negatively on realism. Continuous communication between therapist and patient during weight modifications might be a crucial element in clinical settings. Therefore, further research on the role of presence (and its sub-dimensions) in VR body image interventions seems required, as the latest reviews did not address this topic (Riva et al., 2019; Horne et al., 2020; Turbyne et al., 2021).

Surprisingly, although participants rated their feeling of virtual body ownership descriptively higher compared to non-personalized avatars (Waltemate et al., 2018; Wolf et al., 2020), their ratings were lower than in prior work using personalized and photorealistic avatars (Waltemate et al., 2018). A reason for the noticed differences could be the particularly body-related nature of our task. Avatars created via body scans have a very high resemblance to the individual but still do not provide a perfect visual replica. In a task highly focusing on body perception, even minor inaccuracies may become noticeable, and participants might focus on these, experiencing a diminished feeling of virtual body ownership. Another factor could be the performed body weight modification leading to a reduced congruence between real and virtual bodies and, consequently, might decrease the feeling of virtual body ownership.

The ratings and especially the qualitative statements on avatar perception reveal similar results, as some of the participants stated their avatar to be uncanny or not fully recognizable as themselves. This raises doubts about the degree of personalization of avatars and whether the creation of highly photorealistic textures is currently necessary (and feasible). Tools such as Virtual Caliper (Pujades et al., 2019) can create in shape personalized avatars using only VR equipment. In conjunction with generic avatar generators, such as Meta Human (Epic Games, 2021), highly realistic avatars with personalized body shapes could be created with less effort. They would not resemble the person perfectly, but this lack of resemblance could make them less uncanny while remaining a still better quality in general. Additionally, a personalization in body shape would be sufficient for simulating body weight changes. However, one counter-argument is provided by Thaler et al. (2018a), who clearly state that the body weight perception of avatars having personalized textures differs from generic ones. To address the question of whether personalization of avatars in our context should be achieved through photorealism or customization, further research seems necessary.

Guidelines for VR Design

- The physical and mental effort for system calibration should be kept as low as possible.
- The animations of embodied avatars should be as authentic as possible and include facial expressions, eye movements, and hand gestures to increase realism and reduce eeriness.
- When using physical controllers, virtual controller representations should be displayed in VR and controlled by the avatar.
- When using personalized avatars, body shape and texture should aim for the highest possible conformity with the user to reduce uncanniness.

6.2.1 User experience of body weight modification

When comparing the subjective rankings of the three modification methods, it becomes apparent that the interaction via virtual objects was the least preferred. It was rated as more demanding and difficult, and less vivid, resulting in lower contentment and overall preference than the other two modification methods. Modification via joystick and gestures were rated rather similarly with a slight preference towards the joystick interaction. The in virtuo ratings of workload match these rankings. While joystick was rated quantitatively most positively, the qualitative analysis shows arguments in favor of gesture interaction, especially in terms of vividness and intuitivity. No impact has been noticed on the feeling of embodiment or performance in body weight estimation, which is particularly important in our context.

Regardless of the interaction method, the lack of body weight modification in relation to different body parts (e.g., abdomen, hips, thighs) and in relation to the composition of the body tissue (e.g., fat or muscle mass) was mentioned. The use of advanced body modification methods, such as those presented by Maalin et al. (2020) or Pujades et al. (2019) could allow for body weight modifications that go beyond using only BMI as a single parameter modifying the whole body's weight. However, having more complex body weight modification methods would also increase the complexity of user interaction.

Guidelines for Body Weight Modifications

- Body weight modifications severely differing from the user's BMI or reaching unrealistic or considered unhealthy ranges should be avoided to reduce alienation.
- Body weight modifications should allow changing the body weight independently on different body parts considering different body tissue compositions.
- Body weight modifications performed directly via a hardware input device or body gestures should be preferred over virtual objects or buttons.

6.3 Body image-related outcomes

The comparison of body awareness between the three modification methods indicated a higher body awareness in joystick interaction compared to gestures and objects. However, the reported effects of the VR exposure on body awareness and affect towards the body were very individual, with participants reporting either a loss or an increase of body awareness during the experience. Future work with an increased sample size is necessary to further investigate the difference between the conditions and whether the individual differences are related to people's overall body awareness, as proposed by Filippetti and Tsakiris (2017). These insights will be crucial to determine what effects can be expected for a target group with low body awareness or negative body image.

In contrast to body awareness, body weight estimations did not differ between body weight modification methods. However, when comparing the accuracy of the type of estimations task, PET provided more accurate estimates than AMT. While estimating a person's weight based on their appearance is not an everyday task, it is surely more common than actively modifying a (virtual) body to a certain body weight. Thus, the difference might originate in the relative novelty of active modification compared to passive estimation. Another reason could be the different phrasing of the task instructions, which has been shown to have the ability to influence body weight estimation (Piryankova et al., 2014b). For both PET and AMT, the accuracy of the body weight estimation depended on the target weight, or in other words, on the deviation between the own real weight and the virtually presented body weight. This effect has been observed priorly for VR body weight estimation tasks (Thaler et al., 2018a; Wolf et al., 2020) and is in line with the so-called *Contraction bias* as described by Cornelissen et al. (2016, 2015). It states that body weight estimates are most accurate around an estimator-dependent reference template (of a body) and decrease with increasing BMI difference from this reference. Thereby, bodies heavier than the reference tend to be underestimated, while lighter ones tend to be overestimated. Results on absolute body weight estimations show that although the average misestimations were comparatively low, they are subject to high deviations and uncertainties, which also has been observed priorly (Thaler et al., 2018a). The reasons for this probably lie in the nature of the task, since estimating body weight seems generally challenging, and body image disturbances are ubiquitous even in the healthy population (Longo, 2017). Qualitative feedback confirms the task difficulty. When further analyzing the absolute body weight estimations, it is particularly noticeable that they seem to be easier and more accurate for increased than for reduced body weight. This is rather unexpected since *Weber's Law* suggests that differences in body weight become harder to detect when body weight increases (Cornelissen et al., 2016). A possible reason for the high uncertainties in the absolute body weight estimations and the contradiction to Weber's law could be the perspective on the avatar offered by the virtual mirror, which mainly shows the front side of the body (Cornelissen et al., 2018). More research on this topic seems required.

Guidelines for Body Weight Estimations

- Body weight estimations capturing the current perception of the real body in VR should be performed at the beginning of an intervention, as the perceptibility of the real body might decrease over time.
- When performing body weight estimations, care should be taken to present the respective body equally from multiple perspectives.
- When analyzing body weight misestimations based on avatars, determining the average accuracy of the misestimations with healthy individuals helps avoid strong influences of the system properties.

6.4 Future research directions

The results of our work raise new research questions for future work. First, the high necessity of communication between therapist and user, potentially leading to breaks in presence, raises the question of the general impact of presence in body image interventions. This is also interesting when it comes to augmented reality, as already recognized by Wolf et al. (2022a).

Second, the observed ratings in body ownership despite using photorealistic, personalized avatars and the feedback on avatar perception leads to the question of how photorealism and personalization should be applied to body image interventions. Future work should explore whether avatars that are less personalized in texture are sufficient for our purpose as they might raise less uncanniness.

Third, the severe individual differences in the report of body awareness and affect towards the body raise the question, of which individual characteristics might predict the effects of a VR-based intervention on both variables.

Fourth, future work should further address the difference between active body weight modification and passive body weight estimation we found in this study. It remains unclear which underlying processes lead to differences between the two tasks and whether they impact differently on body image. Similar counts for the observed differences in body weight misestimations for avatars with decreased or increased body weight.

Finally, although our current work is situated in the context of body image disturbances, it aimed to test the usability and user experience of our application regardless of the target population in a non-clinical setting. For subsequent work, we suggest directly incorporating our gained knowledge by considering the participants' feedback and the derived guidelines and testing the system with the intended target population in a feasibility study. To further improve the system in direction of an appropriate clinical setting, technical advancements, like low-cost avatar reconstruction techniques (Wenninger et al., 2020; Bartl et al., 2021), should be incorporated and domain expert opinions, like recently summarized by Halbig et al. (2022), further considered.

6.5 Limitations

Our system implementation and evaluation still have limitations. As stated earlier, some of our participants described mixed feelings toward their personalized avatar and a lack of similarity between their avatar's face and their own. Including animations of facial expressions and eye movements could help increase the association with one's avatar. However, previous work on facial animations has shown only little effect on the perceived embodiment (Gonzalez-Franco et al., 2020; Döllinger et al., 2022). Improving the scan quality in the facial area, i.e., by using more cameras in the facial area, could improve this problem.

While modifying the body weight of the personalized avatars, we keep parts of the face region fixed (see Figure 3). This does not completely accurately model weight gain/loss in this region, as the soft tissue in this area of the face changes with varying body weight (De Greef et al., 2006). Other methods (Piryankova et al., 2014a; Zhao et al., 2018; Tang et al., 2021) deform the whole face region or regularize the deformation of a region similar to ours (Xiao et al., 2020). These methods, however, produce other undesirable effects such as changing eye socket shape or pupillary distance due to the fact that the underlying statistical model produces one direction of change that is applied to all avatars. As the data measured by De Greef et al. (2006) shows, the soft tissue thickness in our fixed region does positively correlate with BMI. However, we note that the correlation for landmarks in our fixed region is smaller than for those outside the fixed region and as such we decided to keep the face region around the eyes, nose, and mouth fixed. As seen in Figure 3, this still produces plausible results while avoiding undesirable changes in face identity. For future work, weight modification models should incorporate information about the underlying bone and muscle structure (Achenbach et al., 2018; Komaritzan et al., 2021) in order to more accurately model changes in soft tissue thickness.

Although our sample included slightly overweight participants, the current design and development phase was limited to students without a diagnosed body image disturbance and predominantly with a BMI in a healthy range. The clinical applicability to our target group, which is already in preparation as part of our ViTraS research project (Döllinger et al., 2019), is one next step after the here presented design and UX optimization phase. Further, given the small sample size of 12 participants and the comparatively narrow range of age, the results cannot be generalized to a wider population. However, the study provides valuable insights into such a system's user experience and facilitates further research.

Overall, the design and development phase would benefit from a larger test sample tailored to the final target group. However, this is not an easy endeavor since it blurs the separation between the usability and user experience tests in the development phases and the clinical application. Hence, it requires closer integration and supervision by therapeutically trained professionals and experts in obesity treatment. Ultimately, this integration would be necessary throughout all steps of technical developments to safeguard against unwanted effects for all participants during the design and development and UX optimization steps. Notably, two participants of our overall healthy sample already showed some emotional reactions when confronted with their modified virtual self. Given the uneasiness some participants felt when their avatar's body weight was modified, further research is needed on how to restrict body weight modifications levels for different populations.

7 Conclusion

In this work, we have presented and evaluated the prototype of an advanced VR therapy support system that allows users to embody a rapidly generated, personalized, photorealistic avatar and modulate its body weight in real-time. Our system already offers numerous positive features and qualities, especially regarding the execution of body scans and an overall enjoyable VR experience. The guidelines for designing VR body image therapy support systems that we derived from our results helps to facilitate future developments in this field.

However, more research is needed for a therapeutic application. Possible areas of investigation include the implementation of photorealism, which may need to be revisited when working on body image. More research is also required on the differences between active body weight modification and passive body weight estimation. Finally, investigations with more focus on the target group and the individual characteristics of future users will be necessary, especially concerning body image distortion, body dissatisfaction, and body awareness.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the Institute Human-Computer-Media (MCM) of the University of Würzburg. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

ND and EW conceptualized large parts of the experimental design, collected the data, performed data analysis, and took the lead in writing the manuscript. EW and DM developed the Unity application including the experimental environment and avatar animation system. MB and SW provided the avatar reconstruction and body weight modification framework. CW and ML conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape study and the corresponding manuscript.

Funding

This research has been funded by the German Federal Ministry of Education and Research in the project ViTraS (project numbers 16SV8219 and 16SV8225). It was further supported by the Open Access Publication Fund of the University of Würzburg.

Acknowledgments

We thank Andrea Bartl for her extensive support when preparing and conducting the body scans, Viktor Frohnapfel for contributing his Blender expertise to our virtual environments, Marie Fiedler for proofreading, and Sara Wolf for her support with our illustrations. We also thank Miriam Fößel and Nico Erdmannsdörfer for their help in preparing the interviews for qualitative analysis. In addition, we would like to thank the project partners from the ViTraS research project for their constructive feedback.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2022.935449/full#supplementary-material

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3 Virtual Reality for Mind and Body: Does the Sense of Embodiment Towards a Virtual Body Affect Physical Body Awareness?

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Author Contributions

Nina Döllinger conceptualized large parts of the experimental design, supervised the data collection, performed the analysis and took the lead in writing the manuscript. Erik Wolf and David Mal developed the Unity application including the experimental environment and avatar animation system. Nico Erdmannsdörfer supported the study conceptualization, the application development an contributed the data collection. Mario Botsch provided the avatar reconstruction framework. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

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ABSTRACT

Mind-body therapies aim to improve health by combining physical and mental exercises. Recent developments tend to incorporate virtual reality (VR) into their design and execution, but there is a lack of research concerning the inclusion of virtual bodies and their effect on body awareness in these designs. In this study, 24 participants performed in-VR body awareness movement tasks in front of a virtual mirror while embodying a photorealistic, personalized avatar. Subsequently, they performed a heartbeat counting task and rated their perceived body awareness and sense of embodiment towards the avatar. We found a significant relationship between sense of embodiment and self-reported body awareness but not between sense of embodiment and heartbeat counting. Future work can build on these findings and further explore the relationship between avatar embodiment and body awareness.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *Empirical studies in HCI*; *HCI theory, concepts and models.*

KEYWORDS

Virtual reality, embodiment, body awareness, mind-body-therapy

ACM Reference Format:
Nina Döllinger, Erik Wolf, David Mal, Nico Erdmannsdörfer, Mario Botsch, Marc Erich Latoschik, and Carolin Wienrich. 2022. Virtual Reality for Mind and Body: Does the Sense of Embodiment Towards a Virtual Body Affect Physical Body Awareness?. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '22 Extended Abstracts), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3491101.3519613

CHI '22 Extended Abstracts, April 29-May 5, 2022, New Orleans, LA, USA

1 INTRODUCTION

Mind-body therapies represent a cluster of therapeutic approaches aiming to improve a person's general state of wellbeing and manage diseases by combining physical and mental exercises. Their idea is to engage patients in mindful self-observation and movement exercises to promote the integration of mind and body, resulting in increased awareness of bodily states and needs. Research on the efficacy of mind-body therapies demonstrates the potential of body awareness in managing a variety of disorders, including chronic pain [4], depression [9], as well as body weight and eating disorders [8, 39].

Based on the assumptions that immersion can positively affect the outcomes of mind-body therapy, recent developments tend to incorporate virtual reality (VR) into the design and execution of mind-body therapies. Various new interventions have been presented over the last decade. The link between body-based interactions in VR and body awareness has recently been discussed by various reviews on VR-based mindfulness [3, 10]. They point out the remaining lack of detail in the scientific results, specifically concerning the link between body awareness and the embodiment of virtual bodies [10]. To address this research gap, our paper explores whether the perceptual shift from the physical body towards a virtual body, also known as the sense of embodiment (SOE) [22], is related to body awareness in a mind-body-oriented task. In a short quantitative study, we examined whether SOE is related to different aspects of body awareness, namely self-reported body awareness and performance in a heartbeat counting task. The contribution of our work is twofold: (a) We provide initial insights into the relationship between avatar perception, namely SOE and a perceived uncanniness of the virtual body, and several aspects of body awareness. (b) We initiate a conversation toward a systematic evaluation of the effects of virtual bodies on body awareness.

2 RELATED WORK

Although there is a wide variety in the execution of mind-body therapies, one central element focuses on the physical body and aims to increase the patient's body awareness. Mehling et al. [29, p. 4] define body awareness as "the perception of bodily states, processes, and actions that is presumed to originate from sensory proprioceptive and interoceptive afferents and that an individual has the capacity to be aware of". Thus, it describes a conscious awareness of body posture signals (proprioception) and internal bodily signals (interoception), including specific sensations like heart activity and complex syndromes like relaxation or pain. Measures for body awareness are divided into body monitoring tasks designed to measure interoceptive accuracy, e.g., heartbeat counting [2], and self-report measures focusing on various aspects of body awareness, e.g., noticing bodily changes or regulating the attention towards the body [28].

Recent developments tend to incorporate VR in general and virtual bodies in particular into mind-body therapies. To systematically investigate the resulting benefits, it is necessary to identify the possible drivers of VR-supported therapy. Wienrich et al. [44] propose a framework for VR-based behavior therapy that efficiently summarizes the possibilities of VR design for therapeutic interventions and provides an overview of potential moderating and mediating responses to VR that should be considered. In addition to the immersive features of VR, such as the virtual environment and their effects on therapeutic target outcomes, their framework highlights the mediating effects of VR-specific perceptions that correspond with these immersive features and psychological drivers associated with the target outcomes. Döllinger et al. [10] adapted this framework for VR-supported mind-body therapy and provided an overview of combinations between design guidelines for mindfulness tasks and basic elements of VR design. They propose that in VR-based mind-body therapies using embodiment of a virtual body, the respective immersive feature is the sensory and behavioral representation of the virtual body. The two potential mediators in this scenario are body awareness as well as SOE towards a virtual body with respect to its proximity to mindfulness [30].

Besides the internal body signals mentioned above, humans permanently process and integrate a mixture of internal and external sensations [29]. VR builds on this perceptual integration. The presented external visual content is designed to carefully match the user's movements and actions and thus to create congruence between the user's external and internal perceptions. This way, a coherent virtual experience is created, which evokes a perception of the plausibility of the VR experience and consequently a sense of presence [24]. When embodying a virtual body, the congruency of visual and physical body perception enables a perceptual shift from the physical to the virtual body, inducing SOE towards the virtual body. Kilteni et al. [22, p. 375] define the SOE as "the sense that emerges when [the body's] properties are processed as if they were the properties of one's own biological body". They define the basis of SOE as a combination of bottom-up and top-down processing. The bottom-up processing of visuotactile, visuoproprioceptive, or visuomotor congruency supported by the visuospatial perspective manipulates external body signals and causes a shift in proprioception, a central element of body awareness. The top-down processing of the virtual body can either lead to a behavioral shift towards associated attitudes and behaviors of a non-personalized virtual body (Proteus effect) [33]. On the other hand, top-down processing leads to increased SOE towards personalized [43] and realistic [23] virtual bodies. However, realism and in specific photorealism of virtual bodies can lead to an unwanted feeling of eerieness (uncanny valley effect) [36], leading to aversion towards the virtual body and to reduced SOE [26].

There exist some investigations on the relationship between body awareness as defined by Mehling et al. [29] and the SOE towards a virtual body to predict applicability in mind-body therapies. Tsakiris et al. [40] showed that an initially high interoceptive accuracy, measured via a heartbeat counting task, negatively affected the SOE towards a virtual arm and hand. In their study, participants who performed better in monitoring and counting their heartbeat reported a lower SOE and vice versa. Reversely, Filippetti and Tsakiris [13] showed that embodiment leads to increased interoceptive accuracy for people with initially low accuracy, again measured via performance in heartbeat counting. In a more recent paper, Heeter et al. [18] revealed a positive impact of self-reported body awareness on the feeling of presence in a virtual environment. However, their environment did not include a virtual body. Similarly, it has been shown that having a virtual body positively affects presence [20, 46], but without measuring body awareness. To our knowledge, there does not exist research on self-reported body awareness and SOE. Additionally, with regard potential effects of uncanniness on body awareness, there has been no research so far.

Both body awareness and SOE arise from the integration of bodily signals. Yet, it remains unclear whether the focus on the visual information when embodying a virtual body can be a helpful tool in mind-body therapies and whether it supports or interferes with establishing a healthy body awareness. A negative effect of SOE on body awareness would severely limit the potential of VR for use in mind-body therapies and preclude one key driver, the Proteus effect. Before investigating the use of virtual bodies that differ from the user, it is necessary to determine whether the SOE to a realistic, personalized virtual body already affects body awareness.

The current paper reveals first insights into the relationship between SOE and body awareness. For our investigation, 24 participants embodied a photorealistic, personalized virtual body while repeatedly performing simple in-VR body awareness tasks in front of a virtual mirror. Then, they performed a heartbeat counting task and self-reported ratings of their SOE, body awareness, and perceived uncanniness of the virtual body. To increase the variance between repeated measures, we varied the presentation of facial movements between repetitions without making an inter-individual assumption about an effect. We assumed that (H1) a trait in body awareness predicts the impact of our task on the current state of body awareness, and (H2) in a VR body movement task, SOE is related to the current state of body awareness. We additionally examined whether top-down processes, like the perceived uncanniness of the virtual body, affected body awareness and whether SOE was related to mindfulness.

3 SYSTEM DESCRIPTION

3.1 Hard- and Software

Our VR setup consisted of an HTC Vive Pro Eye HMD, two hand-held Valve Index controllers (Knuckles), and three HTC Vive Trackers 3.0, attached to the hip and each foot. For our purposes, the hardware components were sufficiently fast and accurately tracked using three SteamVR Base Stations 2.0 [31]. The HMD provided participants a resolution of 1440×1600 px per eye with a total field of view of 110° running at a refresh rate of 90 Hz. The participants' finger poses were tracked by the built-in proximity sensors of the Knuckles, their eye movements were captured by the HMD's built-in eye-tracking running at 120 Hz with an accuracy between 0.5° and 1.1° and end-to-end latency of around 80 ms [37], and their voices were recorded via the HMD's built-in microphone. The participants' facial expressions were not tracked. The setup was driven by a high-end VR-capable PC running our application fluently. For heartbeat measures, we used the Empatica E4 smartwatch [11].

The system was implemented using Unity 2020.3.11f1 LTS [41]. All VR-specific hardware was integrated using SteamVR version 1.16.10 and the corresponding Unity plugin version 2.7.3 [42]. For calculating the avatar's general body pose, we used the Unity plugin FinalIK version 2.0 [34] in conjunction with the system architecture introduced by Wolf et al. [45]. Eye animations were integrated using the Vive SRanipal runtime and SDK version 1.3.2.0. For implementing lip-sync, we used the Virtual Human Project toolkit [16]. All questionnaires were completed via LimeSurvey 4 [25].

3.2 Virtual Environment

We realized the virtual environment of our study by adapting an office room, initially obtained from the Unity Asset Store [1], to create a neutral and peaceful surrounding allowing for relaxation and self-awareness. In VR, a virtual full-body mirror was located on a wall at a distance of 1 m from the participant's position. We implemented the virtual mirror using a custom-written planar reflection shader. A marker on the floor of the virtual environment indicated the correct position for the participants during the study.

3.3 Avatar Generation and Animation

We generated photo-realistic and personalized avatars of the participants using the avatar reconstruction pipeline originally introduced by Achenbach et al. [1]. The pipeline first generates a dense point cloud of the participant's body using 94 high-quality images taken simultaneously from different perspectives. It further converts the point cloud into a fully rigged and textured mesh object, including blend shapes for facial expressions that can immediately be imported as a humanoid avatar into Unity. To induce SOE, the avatar was animated from an egocentric perspective according to the participant's movements in real-time using Unity's avatar animation system. For this purpose, we transferred the generated body and finger pose as well as the eye and lip movements to the participant's avatar using a custom-written retargeting script. The script pre-processes the raw data received from the tracking systems and maps it to the data structures required for proper avatar animation.

[1]https://assetstore.unity.com/packages/3d/props/interior/manager-office-interior-107709

Figure 1: The figure shows a participant's egocentric view while performing the "rotation" task within the virtual environment. The mirror reflects its embodied and personalized avatar.

4 METHODS

Before conducting our study, we obtained ethical approval from the ethics committee of the Human Computer Media institute of the University of Würzburg with no further obligations.

4.1 Participants

A total of $N = 24$ volunteers participated in our investigation (8 male, 16 female). The participants were either undergraduate students ($n = 15$), employees ($n = 5$), currently unemployed ($n = 2$), self-employed ($n = 2$), and were granted either credit points or 30 euros for their participation. The mean age of participants was $M = 29$ years ($SD = 12.17$). Most participants ($n = 19$) stated to have less than three hours of experience in VR and had no experience with photorealistic, personalized avatars ($n = 22$).

4.2 Measures

As dependent variables for the perception of the virtual body, we measured (1) *SOE* and (2) the *perceived uncanniness of the virtual body*. As dependent variables for body awareness, we measured (3) *self-reported body awareness* together with a measure for *mindfulness* and (4) employed a heartbeat counting task measuring *interoceptive accuracy*. Before answering (1) and (2), participants were briefed to answer the questionnaires concerning their virtual body. Before answering (3), participants were briefed to answer the questionnaire about their physical body. Regarding (4), we calculated the difference between the real heartbeat and the estimated heartbeat count for each heartbeat measure (HCT error), as well as the difference of HCT error between pre-VR and post-VR measures (HCT change). As control variables, we included a measure for *trait body awareness* and captured symptoms for *simulation sickness*. The operationalization of the variables can be found in Table 1.

Table 1: The table shows the measures that are included in the analysis of this paper and the abbreviations used in the following.

Variable	Measure	Dimensions
Sense of embodiment	**VEQ**: Virtual Embodiment Questionnaire [35]	Body ownership, agency, change
Perceived uncanniness	**UVI**: Uncanny Valley Index [19]	Humanness, attractiveness, eerieness, spine-tingling
Self-reported body awareness	**SMS**: State Mindfulness Scale [38]	Body
Mindfulness	**SMS**: State Mindfulness Scale [38]	Mind
Interoceptive accuracy	**HCT**: Heartbeat Counting Task [2, 14]	Error: real vs. estimated count, change: post-VR vs. pre-VR
Trait body awareness	**MAIA**: Multidimensional Assessment of Interoceptive Awareness, Version 2 [28]	Total score
Simulation sickness	**SSQ**: Simulator Sickness Questionnaire [21]	Total score

4.3 In-VR Tasks

To elicit a feeling of body awareness and SOE, the participants performed various body movement exercises in front of a virtual mirror (see Figure 1). All exercises were based on Gyllensten et al. [17]'s description of Basic Body Awareness Therapy (BBAT) exercises. We included slightly shortened versions of the exercises *standing*, *rotation*, *wave*, and *push*. They were performed in a standing position and designed to stimulate different muscle groups. Participants were instructed to stand still and focus on perceiving their posture (standing). Subsequently, they were asked to rotate their torso (rotation), to perform rocking movements with their legs while letting their arms swing (wave), and to push their hands forwards while standing in a step position (push). For a more detailed description of the exercises, we refer to the work of Gyllensten et al. [17]. After instructing a movement task, we added the instruction to repeat the movement for 30 seconds until the next exercise was presented. Additionally, participants were instructed to focus on the stimulation of their muscles during the tasks rather than on their performance and to express their feelings during the exercises.

4.4 Procedure

The study followed the procedure illustrated in Figure 2. It was divided into scan and execution, performed on two different appointments. To increase the visual similarity between the participants and their virtual body, we asked them to wear the same clothing to both appointments. In the scan appointment, participants first received information about the local COVID-19 regulations and the experimental procedure and signed consent for body scan and participation. Then, the experimenter assessed the participant's body measures and performed the body scan following the local workflow for body scanning and avatar generation. After the body scan, participants answered demographic questions and further questions about their prior VR experiences. Finally, they performed the heartbeat counting task for the first time. While performing the task, participants were sitting in a relaxed position and counted their heartbeat continuously. For 60 seconds, the heartbeat was measured without telling participants the time frame. The scan appointment lasted $M = 25$ minutes.

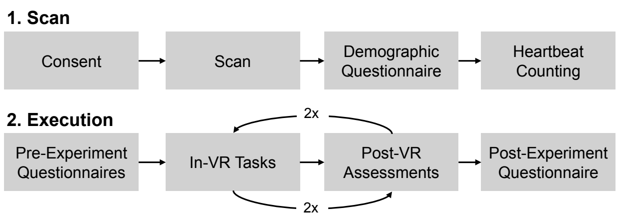

Figure 2: The chart shows the experimental procedure for both appointments.

In the execution appointment, participants first answered the pre-experiment questionnaires, MAIA and SSQ, followed by two VR sessions. The two VR sessions varied in the visual representation of the virtual bodies' facial expressions (no facial expressions vs. eye and mouth movements), designed to increase variance in embodiment ratings. They were presented in counterbalanced order. Each VR session lasted 12 minutes. After a calibration of the avatar animation system, the participants were asked to describe their virtual body and express their feelings towards it, followed by the in-VR tasks. All in-VR asks were instructed via pre-recorded audio instructions. After the in-VR tasks, the participants answered SMS, VEQ, UVI, and performed heartbeat counting (post-VR assessments). Then, the VR exposure started for a second time. At the end of the session, participants answered the SSQ (post-experiment questionnaire). The execution appointment lasted $M = 68$ minutes.

5 RESULTS

All tests were performed using the statistics software R, version 4.1.0 [32]. The correlative results are shown in Table 2. In a pre-post comparison of the SSQ scores, we first tested whether participants had to be excluded due to simulator sickness. Results showed a maximum pre-post difference of 29.9 pts ($Md = 7.48, M = 15.27, SD = 18.25$) and a maximum post-measure of 74.8 pts for one participant. Therefore, none of the participants was excluded due to simulation sickness.

To test hypothesis H1, we analyzed the relation between trait body awareness (MAIA) and self-reported body awareness after the VR exposure (SMS body) and the relationship between interoceptive accuracy in the first heartbeat counting task (HCT error) and interoceptive accuracy increase after the VR exposure (HCT change). We calculated average scores for SMS body and HCT change over the two post-VR assessments. Subsequently, we calculated two simple linear regressions to predict SMS body based on the MAIA total score and HCT change based on the initial HCT error. In line with our hypothesis H1, MAIA ratings positively

Table 2: The table shows the results of the repeated measures correlations for self-reported body awareness (SMS body), interoceptive accuracy (HCT change) and mindfulness (SMS mind).

	SMS body				HCT change				SMS mind			
	r	*df*	*p*	95 % *CI* [*LL, UL*]	*r*	*df*	*p*	95 % *CI* [*LL, UL*]	*r*	*df*	*p*	95 % *CI* [*LL, UL*]
VEQ body ownership	.58	23	.002	[.22, .80]	.15	23	.475	[-.28, .53]	.42	23	.039	[.004, .71]
VEQ agency	.48	23	.014	[.09, .75]	-.13	23	.512	[-.52, .29]	.27	23	.196	[-.16, .61]
VEQ change	.26	23	.203	[-.17, .61]	.08	23	.715	[-.35, .47]	-.38	23	.064	[-.68, .04]
UVI humanness	.37	23	.070	[-.05, .68]	.05	23	.827	[-.37, .45]				
UVI attractiveness	.34	23	.092	[-.08, .66]	.12	23	.570	[-.31, .51]				
UVI eerieness	-.16	23	.446	[-.54, .27]	.32	23	.116	[-.10, .65]				
UVI spine tingling	.18	23	.387	[-.25, .55]	-.03	23	.899	[-.43, .39]				

predicted SMS body ratings in a significant regression equation, $F(1, 22) = 13.56, p = .001, R^2 = 0.35$. The mean scores in SMS body were equal to $1.81 + 0.64 \cdot$ (MAIA). SMS body increased 0.64 pts for each scale point in MAIA ratings. Additionally, HCT error in the first appointment negatively predicted HCT change in a significant regression equation, $F(1, 22) = 27.26, p < .001, R^2 = 0.53$. Thus, the HCT change was equal to $7.28 - 0.66 \cdot$ (initial HCT error). HCT change decreased 0.66 pts for each miscounted heartbeat in the initial HCT error.

To test hypothesis H2 on the relationship between SOE (VEQ) and body awareness (SMS body, HCT change), we analyzed the results of the two post-VR assessments on an intra-individual level. We calculated repeated measures correlations between SMS body and VEQ dimensions as well as HCT change and VEQ dimensions following the instruction of Bakdash and Marusich [5]. The correlative results are shown in Table 2. Partly in line with our hypothesis H2, the SMS body correlated positively with two of the three VEQ dimensions, body ownership, and agency, but not with VEQ change. The two significant regressions are depicted in Figure 3. Contrary to our assumptions, HCT change was not related to VEQ ratings.

Finally, we exploratory tested for a relationship between self-reported body awareness (SMS body) and perceived uncanniness of the virtual body (UVI), between interoceptive accuracy (HCT change) and perceived uncanniness of the virtual body (UVI), and between mindfulness (SMS mind) and SOE (VEQ). Here too, we used repeated-measures correlations. Neither the calculated correlations on SMS body and UVI nor the calculated correlations of HCT change and UVI revealed a significant relationship between self-reported body awareness or interoceptive accuracy and humanness, attractiveness, eerieness, or spine-tingling. The exploratory analysis of the SMS mind and VEQ revealed a significant positive correlation between SMS mind and VEQ body ownership. The intra-individual relationship between SMS mind and VEQ agency as well as SMS mind and VEQ change were not significant.

6 DISCUSSION

Our experiment aimed to gain first insights into the relationship between the SOE and different measures of body awareness in an in-VR body awareness task. We found a positive relationship between a trait in body awareness and self-reported body awareness after our task, indicating a good match between the two measures. Further, we could partly replicate the results of Filippetti and Tsakiris [13]. In line with their work, we found an impact of initial performance in the heartbeat counting task on performance improvement. Consequently, participants with initial good performance were less affected by the VR exposure. However, this result is easily explained by the fact that the performance of some participants was initially already very high, leaving only little room for improvement.

When comparing the SOE with self-reported body awareness on an intra-individual level, we found a positive relation between VEQ body ownership and VEQ agency with SMS body and between VEQ body ownership with SMS mind. When reporting an increased SOE in one VR session compared to another, participants rated both their body awareness and mindfulness higher. This relationship indicates potential for the use of embodiment and SOE in mind-body therapies and is in line with prior work on the positive impact of SOE on wellbeing [27]. Further, it raises the question, of whether the factors that affect SOE, such as visuomotor congruency, visuoproprioceptive congruency are equally important for the maintenance or increase of body awareness and mindfulness in a VR application. The results regarding the perceived uncanniness of the virtual body measured via the UVI did not reveal a significant relation with body awareness. However, we found a tendency towards a positive relationship between self-reported body awareness and the two dimensions of humanness and attractiveness. These results indicate that a rating of the own virtual body as more human or more attractive could be related to higher perceived body awareness. It delineates a possible influence of top-down processes on body awareness in virtual environments, similar to the effects of visual virtual body representations, e.g., personalization, on SOE [22, 43].

The results of the heartbeat counting task differ widely from the results of the self-reported body awareness, as we could find neither a relation between HCT change and SOE nor between HCT change and UVI. This outcome is in line with former investigations on the relationship of self-reported body awareness and interoceptive accuracy that showed the independence of self-report body awareness measures and body monitoring tasks [7, 12]. However, it contradicts the results of Tsakiris et al. [40], who found a negative impact of SOE on the performance in heartbeat counting, or the results of Filippetti and Tsakiris [13], who found a positive effect of SOE on interoceptive accuracy, at least for participants with low initial performance.

The findings of this study have to be interpreted with consideration of some limitations. First, we neither included a baseline

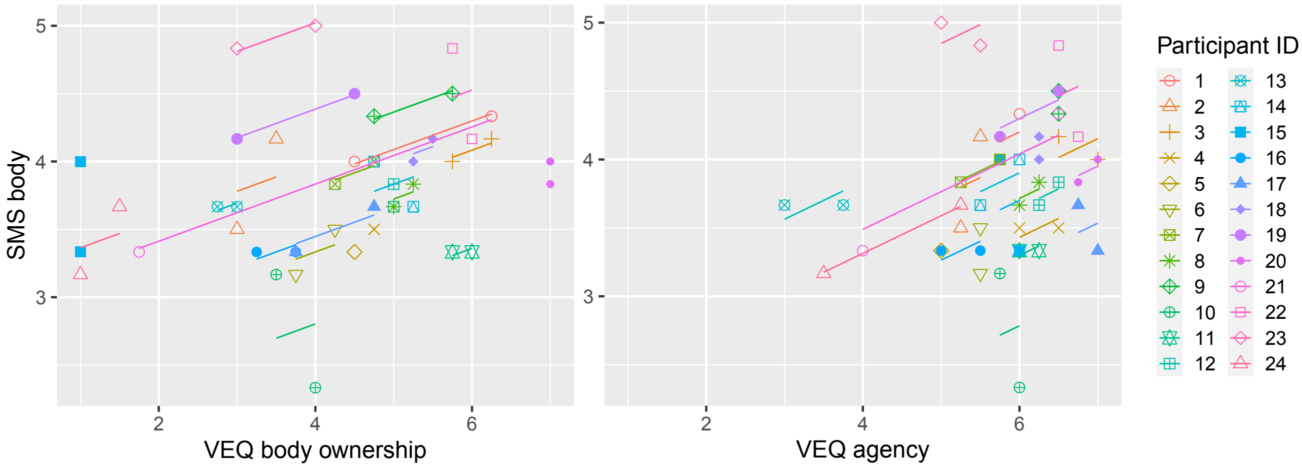

Figure 3: The chart shows the intra-individual relation between the two dimensions body ownership and agency (VEQ) and the self-report measure for body awareness (SMS body). Each dot represents one of the two post-VR assessments of a participant. Ratings of the same participant are given the same color, with corresponding lines to show the model fit for each participant. It depicts a consistent intra-individual dependency between sense of embodiment and body awareness over two VR exposures. A higher report in either agency or body ownership is associated with a higher rating in body awareness and vice versa.

condition without a virtual body nor outside VR. While our participants did not report discomfort during the exercises, future work should seek to validate them for usage in VR, as wearing the headset itself could have an impact on its outcomes concerning body awareness. Second, we did not manipulate the visuomotor or visuoproprioceptive congruency for a systematic variation in SOE. Gonzalez-Franco et al. [15] found that facial animations can systematically affect SOE towards virtual faces. However, they only found an effect on one single item, and the focus of our in-VR task was on full-body movements instead of focusing on facial expressions. Future investigations should investigate whether having a virtual body is per se beneficial in mind-body-oriented VR applications. Further, it should focus on varying embodiment conditions using more pronounced and task-relevant variations. Since personalized avatars become more affordable [6], it may also be worth exploring the role of avatar personalization in this context. Another limitation is that we assessed the heartbeat counting task on two different appointments, which may have increased variance in the data. However, we could still show that the HCT error in the initial assessment predicted the following HCT change after the VR exposure and thus replicated earlier results [13]. Finally, there are some limitations to our analysis. We examined several variables on SOE, the perceived uncanniness of the virtual body, and body awareness, leading to a large number of significance tests and thus possibly to a higher probability of false-positive results. However, given that this experiment is a first step in exploring the relationship between virtual body representation, SOE, and body awareness, we claim the importance of capturing small effects.

7 CONCLUSION

In this work, we investigated the relationship between body awareness and the sense of embodiment towards a virtual body. We found a positive correlation between SOE and self-reported body awareness and between SOE and mindfulness, indicating a potential for embodiment in virtual mind-body therapies. We further found a tendency for a positive relationship between perceived humanness and attractiveness of the virtual body on self-reported body awareness, indicating the importance of pleasant virtual bodies. This finding is specifically interesting for a potential use of non-personalized virtual bodies, e.g., when exploring a potential Proteus effect. Finally, we found that the performance in a heartbeat counting task was neither related to SOE nor any rating towards the virtual body, indicating that self-reported body awareness and body monitoring performance in VR require different manipulations. Future work can build on these results and investigate more deeply the potential of the embodiment of different types of virtual bodies as support for mind-body therapies.

ACKNOWLEDGMENTS

This research has been funded by the German Federal Ministry of Education and Research in the project ViTraS (16SV8219).

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4 Are Embodied Avatars Harmful to our Self-Experience? The Impact of Virtual Embodiment on Body Awareness

Döllinger, N., Wolf, E., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023). Are embodied avatars harmful to our self-experience? The impact of virtual embodiment on body awareness. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. doi: 10.1145/3544548.3580918

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Author Contribution

Nina Döllinger conceptualized the experimental design, adapted the Unity application for the experiment, provided the data collection, performed the analysis and took the lead in writing the manuscript. Erik Wolf developed the Unity application including the experimental environment and avatar animation system. Mario Botsch provided the avatar reconstruction framework. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

Are Embodied Avatars Harmful to our Self-Experience? The Impact of Virtual Embodiment on Body Awareness

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Figure 1: A participant in front of a mirror: the virtual replicas (left) were designed to match the real setting (right).

ABSTRACT

Virtual Reality (VR) allows us to replace our visible body with a virtual self-representation (avatar) and to explore its effects on our body perception. While the feeling of owning and controlling a virtual body is widely researched, how VR affects the awareness of internal body signals (body awareness) remains open. Forty participants performed moving meditation tasks in reality and VR, either facing their mirror image or not. Both the virtual environment and avatars photorealistically matched their real counterparts. We found a negative effect of VR on body awareness, mediated by feeling embodied in and changed by the avatar. Further, we revealed a negative effect of a mirror on body awareness. Our results indicate that assessing body awareness should be essential in evaluating VR designs and avatar embodiment aiming at mental health, as even a scenario as close to reality as possible can distract users from their internal body signals.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Laboratory experiments*; *Empirical studies in HCI*.

KEYWORDS

Sense of embodiment, virtual reality, interoception, body ownership, agency, body perception, virtual humans

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04.
https://doi.org/10.1145/3544548.3580918

ACM Reference Format:
Nina Döllinger, Erik Wolf, Mario Botsch, Marc Erich Latoschik, and Carolin Wienrich. 2023. Are Embodied Avatars Harmful to our Self-Experience? The Impact of Virtual Embodiment on Body Awareness. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3544548.3580918

1 INTRODUCTION

Every living being on our planet has a body. Our bodies enable us to interact with our environment while continuously providing information about that environment, our movements and posture, our internal states, and our subjective well-being. A core research question of cognitive science deals with the perception of our body. Embodiment, the experience of simultaneously being and having a body [71], depicts a research perspective that defines the body as a prerequisite for mental processes and examines them concerning their bodily foundation and expression. The body is consequently defined as an elementary component of human experience and self-perception [72]. Recent discussions on VR, avatars, and the metaverse raise an additional question: What happens to our bodily experience when we suddenly have to act and interact through a digital replica instead of our well-known and familiar body?

VR can replace a person's physical body with an arbitrary virtual self-representation (virtual body or avatar) that can be controlled and used to interact with a virtual environment. Through virtual bodies, or rather the discrepancy between the virtual and the physical body, it is possible to manipulate various aspects of body perception. For example, being represented by thinner or larger virtual bodies can alter the perception of body size [48, 50, 76], extended or misaligned arms and legs to an altered estimation of one's reaching distance [37], or increased latency to an altered perception of one's body weight [33]. Inspired by early experiments on bodily illusions, especially the Rubber Hand Illusion (RHI) [8], a substantial fraction of VR research deals with the question of what it means to have a body, how it feels to possess or embody it – and to what extent a virtual body is perceived as a part, extension, or substitute of the physical body. The term embodiment extends thereby from having and controlling a physical to a virtual body. It is often operationalized as a sense of embodiment (SoE), or the "conscious experience of self-identification (body ownership), controlling one's body movements (agency) and being located at the position of one's body in [a virtual] environment (self-location)" [52, p. 3547].

One aspect of body perception of particular interest in embodiment research is body awareness, the ability to recognize subtle internal body signals [45]. Body awareness is a core element of our self-perception. It is related to psychological and physical well-being and affects the management of chronic medical conditions such as chronic pain [24], eating disorders [35], or anxiety and depression [49]. Therefore, the application of VR in various areas of life raises the question of the extent to which the embodiment of virtual bodies poses not only a chance but a risk to our body awareness. Is the replacement of our own body with a virtual body disturbing? Or can it even support body awareness by drawing attention to the body through external stimulation? The embodiment of artificial body parts has been shown to interact with body awareness. Filippetti and Tsakiris [19] found that the RHI can positively affect body awareness, but identification with an unfamiliar face leads to a reverse effect. Döllinger et al. [15] discovered a positive correlation between SoE toward a personalized virtual body and body awareness. However, it has not been investigated systematically to what extent the embodiment of a virtual body affects body awareness compared to interactions with one's physical body. Further, there has been no research on the effect of the confrontation with one's (virtual) mirror image, a common tool in the embodiment of virtual bodies [32], on body awareness.

In a 2x2 mixed design study with 40 participants, we investigated how embodying a photorealistic virtual body affects body awareness compared to interacting with one's physical body. Participants performed a series of body-based movement exercises in a real and virtual laboratory. While they viewed, controlled, and explored their physical bodies in the real environment, they embodied a photorealistic personalized virtual body in VR. During the experience, they were either confronted with an additional third-person perspective on their body via a (virtual) mirror or not. We recorded their self-reported body awareness, SoE, and performance in a heartbeat counting task as dependent variables. In doing so, we investigate the extent to which the two factors, virtuality and perspective, affect body awareness and the role of the SoE within these effects. Our work empirically connects body awareness and SoE in VR and compares how the sense of embodiment toward virtual bodies differs from that toward real bodies. Our results allow us to infer for VR design whether even a VR scenario that is as close to reality as possible can distract users from their physical bodies. In addition, they challenge the role of a mirror in the design of VR-based embodiment and (mental) health scenarios.

2 RELATED WORK

2.1 Body Awareness in Mind-Body Therapy

Our body constantly gathers, processes, and filters information about our environment. It is sensitive to the outside temperature, the intensity of touch, or the noise of our surroundings. In addition to external signals from our environment, signals from inside the body maintain our self-awareness [63]. The processing of these internal body signals, especially the interoceptive and proprioceptive signals, is called body awareness. It is defined as the "subjective, phenomenological aspect of proprioception and interoception that enters conscious awareness and is modifiable by mental processes such as attention, interpretation, evaluation, beliefs, memories, conditioning, attitudes, and affect" [45, p. 4]. Therefore, body awareness is a central part of perceiving the body's sensations and includes the perception of various internal body signals, such as hunger and heart activity or other more complex perceptive syndromes. It is often captured via self-reports or operationalized as interoceptive accuracy (IAC) and assessed via heartbeat-counting tasks.

Body awareness is closely linked to mental health and subjective well-being [28] and is negatively related to symptoms of depression [49], eating disorders [35], or migraine [55]. On the other hand, body awareness dysfunctions are associated with increased suicidal thoughts and actions [30]. Following these findings, Gibson [25] proposed in a recent discussion that a strengthened IAC or body awareness accounts for the benefits of mindfulness practice in different research. The processing of the body's internal signals has become the focus of several therapeutic approaches, so-called mind-body therapies, aiming to integrate mind and body awareness into daily life via breathing, meditation, or movement exercises [46]. Although the practical application of body awareness in therapy varies widely, in a qualitative study on the definition of body awareness in therapy, Mehling et al. [46] found a great deal of commonality in understanding body awareness among practitioners. Therapists have defined body awareness in two ways, as a core element of integrity and an essential part of self-awareness and as an individual's capacity and ability for embodiment.

Therapeutic approaches aiming to increase or adapt body awareness mostly rely on modifying body awareness via attention regulation. Directing attention to external body signals can facilitate the processing of interoception [3, 42]. Especially in the field of mindfulness, some developments and design ideas have been proposed to integrate VR into mind-body therapy approaches. In this context, VR allows arbitrarily adapting the visible environment or augmenting feedback to body movements or physiological measures using virtual stimuli. While research in this area has predominantly relied on mindfulness, the influence of virtual bodies on body awareness could provide new insights into the mechanisms of body awareness and embodiment and how virtual stimuli could help maintain or manipulate body awareness in a virtual therapy scenario [4, 14].

2.2 Embodying Virtual Bodies

VR experiences rely on supplementing, modifying, or replacing a particular part of body signals with virtual stimuli. Typically, this is done by displaying visual stimuli while excluding visual information from the real environment. Adapting visual movements to the user's actions establishes a state of congruence between the digital (visual) and non-digital (proprioceptive, vestibular, and kinesthetic) stimuli [39]. Upon meeting this state, the virtual experience is perceived as plausible and thus elicits a sense of presence. When embodying a virtual body, the congruence of a virtual body's behavior and look can lead to plausibility [43] and a perceptual shift towards the virtual body. Kilteni et al. [36, p. 375] define this state as the Sense of Embodiment (SoE), "the sense that emerges when [the body's] properties are processed as if they were the properties of one's own biological body". In the context of our work, the question arises whether one's body perception is influenced when the visual body signals do not come from the own body. Through bottom-up processing of congruent visuotactile or visuomotor stimulation, the perception of a virtual body is integrated into one's physical body perception causing the virtual body to be perceived as a part, extension, or substitute of the physical body. A typical method to enhance the SoE towards a virtual body is the mirror metaphor [32]. By adding a mirror to the virtual environment and consciously juxtaposing the user with their virtual mirror image, the effect of visuomotor or visuotactile congruence is intended to be reinforced [57].

2.3 The Impact of Avatar Embodiment on Body Perception

In VR, external and internal body signals may be overridden or suppressed by the external signals presented through the embodiment of virtual bodies. For example, in a study on temperature sensitivity in the palm, Llobera et al. [41] showed that external temperature stimuli are processed less dominant during the embodiment of a virtual body. In their study, half of the participants were presented with a visuomotor congruent virtual body whose movements and posture corresponded to their own. In contrast, the other half of the participants were presented with an incongruent representation. It turned out that participants in the congruent condition were less sensitive to temperature differences. The authors stated a distraction by the visual stimuli could not explain this effect but an integration of the congruent virtual body into the own body perception. Concerning the processing of internal body stimuli, Kasahara et al. [33] showed in a study on visuomotor congruence that delays in the body movement of a virtual body produced a feeling of heaviness in one's physical body. In contrast, faster virtual body movements produced a feeling of physical lightness. In addition to the visuomotor congruence between the physical and the virtual body, it has been investigated to what extent an inconsistency between dimensions of body parts impacts body perception, for example, proprioception and the perception of one's body position and dimensions. Van der Veer et al. [68] demonstrated that the positioning of virtual body parts relative to the physical body might lead to a proprioceptive shift when estimating the position of physical body parts. Kilteni et al. [37] showed that the length of virtual arms influences the perception of one's own reach and body space. With remark to an embodiment scenario with virtual bodies, various works demonstrated that embodying virtual bodies of different sizes impacts body weight perception and the estimation of one's body size [48, 50, 76].

However, it remains unclear whether these influences on the different aspects of body perception are equivalent to an impact on body awareness. When considering the goal of mind-body interventions, strengthening the connection between body and mind, the question arises of whether VR can be a suitable tool for mental health interventions. Suppose body perception is affected by those external stimuli. Does the embodiment of virtual bodies and the associated distraction from the real body towards a virtual body have a disruptive effect on body awareness?

2.4 The Relationship between Body Awareness and Sense of Embodiment

2.4.1 Body Awareness Affects the Sense of Embodiment. Working with artificial bodies is integral for exploring body awareness and embodiment, as it allows us to manipulate and investigate what it means to feel, own, or control a body. Consequently, literature on this topic initially addresses how body awareness, or IAC, affects the adoption of SoE towards artificial or virtual bodies or body parts, mainly using the Rubber Hand Illusion as a tool of exteroceptive manipulation. In this method, visuotactile congruent stimulation and simultaneous visual occlusion of the physical hand produce an SoE toward an artificial hand. Tsakiris et al. [63] discovered a negative relation between IAC and accepting such external stimuli. Based on the RHI, they investigated to what extent the individual IAC affected the SoE towards the artificial hand. They found that the RHI affected individuals with low IAC more than individuals with high IAC. The authors concluded that the influence of external stimuli is more substantial when the individual processes fewer interoceptive signals. In an experiment on body awareness, IAC, and the autism spectrum, Schauder et al. [54] replicated the results of Tsakiris et al. [63]. Again, IAC negatively affected the SoE towards a rubber hand, supporting the proposed trade-off between internal and external cue processing. While the two previous experiments focused on the embodiment of generic hand models, Tajadura-Jiménez and Tsakiris [61] investigated the influence of IAC on SoE towards an unfamiliar face in a so-called enfacement illusion. In their study, individuals with low IAC were more likely to be influenced by the interaction with the face and to show more SoE towards this face than individuals with low IAC. The influence of self-reported body awareness on susceptibility to the RHI has also been investigated, but no impact was found [10]. In an embodiment scenario with virtual bodies in VR, Dewez et al. [13] further investigated how self-reported body awareness influences SoE towards a generic virtual body. They found a descriptive but no significant relationship between body awareness and SoE, similar to the relationship between IAC and SoE.

2.4.2 Embodiment of Virtual Bodies Affects Body Awareness. In addition to the studies on the impact of body awareness and IAC on SoE, a few investigated the reverse research question of how the embodiment of an artificial body affects body awareness. Filippetti and Tsakiris [19] investigated the extent to which visuotactile congruence and a resulting variation in SoE affected body awareness using the RHI. They found that congruence of visual and tactile stimulation positively affected SoE and body awareness. Participants performed better in an IAC task after a high congruence condition than after a low congruence condition. A pre-post comparison revealed an increase in performance in the IAC task, but only for participants with a lower IAC at baseline. Thus, individuals with initially lower accuracy in detecting internal bodily sensations seem to benefit from the exteroceptive body signals of a congruent RHI task. In addition, Filippetti and Tsakiris [19] report an adverse effect of visuotactile congruence in an enfacement task when using the participant's face but not when using a generic face. When embodying a picture of their own face, individuals in the congruent condition achieved lower performance in IAC than individuals in the incongruent conditions. Overall, the enfacement illusion had a negative main effect on IAC for participants with higher IAC at baseline. This result contrasts with the results on the RHI. It indicates that including mirror exposure in the embodiment of artificial bodies might lead to different effects on body awareness than when the face of the artificial body is not visible. In the context of VR, Döllinger et al. [15] tested whether the SoE towards a photorealistically personalized virtual body was related to self-reported body awareness or IAC. They found a positive relationship between SoE and self-reported body awareness but not between SoE and IAC.

2.5 Summary and Contribution

The processing of exteroceptive signals from the RHI or embodiment of virtual bodies might partially compete with the processing of internal body signals and thus limit body awareness [54, 63]. The presented research highlights the importance of visuotactile or visuomotor congruence in the embodiment of artificial bodies or body parts to maintain or even strengthen body awareness. However, especially when embodying artificial faces, visuotactile congruence does not rule out a negative influence on body awareness [19]. During enfacement illusions, congruence might even have an adverse effect. In summary, prior work suggests a relationship between IAC and SoE and between self-reported body awareness and SoE. However, research is still pending on how VR affects body awareness and IAC compared to reality. It further needs to be investigated to what extent the presented perspective on a personalized virtual body affects the perceived body awareness and IAC.

To address these research gaps, we present a study investigating the effects of having a mirror image in a body awareness movement task in VR. Additionally, we investigate to what extent the embodiment of a highly personalized, photorealistic virtual body affects body awareness and IAC. In a 2×2 design, we evaluated the effects of virtuality and perspective on body awareness. Our participants performed movement exercises from Basic Body Awareness Therapy [27] either in a laboratory of the University of Würzburg or in a virtual model of that laboratory in VR in counterbalanced order (virtuality). When in VR, they embodied a virtual replica of themselves. Half of our participants performed the exercises in front of a mirror, and the second half performed them without a mirror (perspective). As dependent variables, we recorded their self-reported body awareness and SoE, measured in experience directly following the performed exercises. Additionally, we assessed their self-reported body awareness, SoE, and IAC measured after leaving the virtual or real laboratory environment. The results of our study intend to provide new insights into the effects of VR on body awareness and, thus, new insights into the relationship between one's virtual and physical body. Based on the work presented above, we hypothesize the following:

- H1.1: The SoE of an individual towards their virtual body in VR differs from the SoE towards their physical body in a real-world environment.
- H1.2: An additional visual perspective on the body, provided by a mirror, has a supporting effect on the SoE.
- H2.1: Even when embodying a photorealistic personalized virtual body, VR affects body awareness.
- H2.2: An additional visual perspective on the body, provided by a mirror, affects body awareness through exteroceptive stimulation.
- H3: The SoE towards a (virtual) body mediates the effects of perspective or virtuality on body awareness.

3 METHODS

3.1 Ethics

We conducted our study according to the Declaration of Helsinki and received approval from the ethics committee of the Institute Human-Computer-Media (MCM) of the University of Würzburg [1]. Given the prolonged exposure to the mirror image, we referred participants during acquisition and after the study to the freely available support services from the Anorexia Nervosa and Associated Disorders organization (ANAD) [2], which they could contact in case they felt uncomfortable about their body shape. Participants were informed in advance about the risks of VR regarding simulation sickness and epilepsy symptoms according to the local VR-usage guidelines. Before entering VR, participants were instructed to report any discomfort they felt during the VR experience immediately. In addition, we set up an area where participants could sit down in silence, hydrate, or lie down if needed.

[1] https://www.mcm.uni-wuerzburg.de/forschung/ethikkommission/
[2] https://www.anad.de/

3.2 Participants

A total of 45 students and employees of the University of Würzburg participated in our study and received either course credit or 30 EUR in return. Ahead of the evaluation, we defined four exclusion criteria queried by self-disclosure. Participants were not eligible when they (1) had visual impairments not compensated by contact lenses, (2) currently suffered from a diagnosed eating or body image disorder, (3) had less than three years of experience with the German language, or (4) reported simulation sickness symptoms during the experiment. We excluded one participant due to their visual impairment and four participants due to technical issues during the VR session ($n = 3$) or heart rate tracking ($n = 1$). Thus, we included 40 participants (25 female, 15 male) in our analysis. The participants were between 19 and 53 years ($M = 22.00$, $SD = 1.48$). Twenty-nine participants had spent less than 5 hours, seven participants had spent 5-10 hours, and 4 participants had spent 10-20 hours in VR. Six participants had never used a VR system before their participation.

3.3 Study Design

Our study was designed in a 2×2 mixed design with the two independent variables *virtuality* and *perspective*. The first independent variable, virtuality, included two experimental conditions performed by each participant: *reality* and *VR*. In reality, the tasks were performed in the local laboratory, while in VR, they were performed in a virtual replica of the local laboratory. The order of the two conditions was counterbalanced. The second independent variable, perspective, varied between participants. Participants performed the tasks described in Section 3.6.1 either *in front of a (virtual) mirror* or *without a mirror*. Thus, participants only received additional external cues about their bodies in the mirror condition. As dependent variables, we assessed the participants' self-reported body awareness and their IAC. As a possible mediator between the independent and dependent variables, we assessed their SoE towards their visible body. As control variables, we captured the participants' body awareness, body consciousness, and IAC prior to our experimental tasks and the two VR-related measures of simulator sickness and avatar uncanniness.

3.4 Apparatus

3.4.1 Hard- and Software. The VR hardware was integrated using SteamVR version 1.16.10 [67] and the corresponding Unity plugin version 2.7.3 [3]. The VR conditions were implemented using Unity 2020.3.11f1 LTS [65]. For calculating the avatar's general body pose, we used the Unity plugin FinalIK version 2.0 [4] in conjunction with the system architecture introduced by Wolf et al. [74].

Our VR setup consisted of an HTC Vive Pro HMD, two handheld Valve Index Controllers (Knuckles), and three HTC Vive Trackers 3.0. One tracker was attached to the hip and one to each foot. All devices were tracked using four SteamVR Base Stations 2.0. The HMD provided participants a total field of view of $108.8 \times 111.4\,^{\circ}$ and a resolution of 1440×1600 px per eye [5]. It ran at a refresh rate of 90 Hz. The participants' finger poses were tracked by the built-in proximity sensors of the Knuckles, while facial expressions were not tracked. The setup was driven by a high-end VR-capable workstation that consisted of an Intel Core i7-9700K CPU, an NVIDIA GeForce RTX 2080 Ti, and 32 GB RAM. To answer the questionnaires outside of VR, participants used an office workstation with a keyboard, mouse, and 24-inch LCD screen. The questionnaires were presented with LimeSurvey 4 [40]. For heart rate measures, we used the Empatica E4 smartwatch [17].

We determined our system's motion-to-photon latency by frame-counting [29, 58, 60]. For this purpose, the video signal output of the graphics card was split into two signals using an Aten VanCryst VS192 display port splitter, one of the signals led to the HMD and the other to an ASUS ROG SWIFT PG43UQ low-latency gaming monitor. The user's movements and the corresponding reactions on the monitor screen were captured using a Casio EX-ZR200 high-speed camera recording at 240 fps. The latency was repeatedly determined (n= 20) by counting the recorded frames between the user's movements and the virtual body's reaction while showing the virtual mirror and was, on average, 64.79 ms ($SD = 8.05$).

3.4.2 Real Environment. The study was performed in a laboratory of the University of Würzburg. In the room's center, a marker on the floor defined the participants' positions during different tasks. Following the guidelines for mirror placement of Wolf et al. [73], a mirror was placed at a distance of 1.5 meters from the participant. Depending on the perspective condition and the task, the mirror either showed the participants' reflection or was turned away. Two speakers stood on the floor next to the mirror to play audio instructions. Two desks were placed on one side of the room next to each other. One contained the questionnaire workstation for the participants. The other contained the VR workstation. To avoid participants' answers being affected by the experimenter's presence, a privacy screen separated the experimenter's workstation from the participants' workstation. Additionally, two privacy screens were placed between the experimenter and the participants during conditions. Thus, the participants could not see the experimenter while performing tasks.

3.4.3 Virtual Environment. We followed Skarbez et al. [56] and provided a virtual environment replicating the real laboratory (see Figure 1) to control environmental influences between the VR and reality conditions. The virtual environment was spatially aligned to the real environment by a custom calibration script. Hence, the position of the marker and the mirror matched in both environments.

3.4.4 Virtual Body. To provide a high similarity between the participants' real and virtual bodies, we used the method for fast generation of photorealistically personalized virtual bodies proposed by Achenbach et al. [1]. Using a custom-built multi-DSLR camera setup, 96 photos of the participants are taken simultaneously. The photos provide the input for generating a dense point cloud of the participants using Agisoft Metashape [2]. It serves as the basis for modifying a fully rigged template mesh originally taken from the Autodesk Character Generator [5] following statistical parameters and non-rigid deformation to accurately replicate the participants' body shape. In a further step, a photorealistic texture is generated that represents the personalized surface of the body. A more detailed explanation of the whole procedure can be found in Bartl et al. [7]. The virtual body was imported into Unity using an FBX-based

[3]https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647
[4]https://assetstore.unity.com/packages/tools/animation/final-ik-14290
[5]https://github.com/PeterTh/ovr_rawprojection

Table 1: In-experience items for SoE, body awareness, and avatar uncanniness.

Variable	Item	Original scale
Sense of Embodiment		
Body Ownership (BO)	It felt like the virtual body was my body.	VEQ [52]
Agency (AG)	The virtual body's movements felt like they were my movements.	VEQ [52]
Change CH	I felt like the form or appearance of my own body had changed.	VEQ [52]
Body Awareness		
Noticing external (NE)	I noticed various sensations caused by my surroundings (e. g. heat, coolness, the wind on my face)	SMS [62]
Noticing internal (NI)	I clearly physically felt what was going on in my body	SMS [62]
Body listening (BL)	I listened to what my body was telling me.	SMS-PA [9]
Attention regulation (AR)	It was easy for me to pay attention to my body.	—
Visual attention (VA)	I focused more on how my body looked than how it felt.	OBCS [47]
Avatar Uncanniness		
Satisfaction	I was satisfied with my body.	—
Discomfort	I felt uncomfortable in my body.	—

custom importer and animated in real-time according to the participants' movements using the hard- and software setup described above. To this end, we used the embodiment system presented by Wolf et al. [74] and evaluated by Döllinger et al. [16].

3.5 Measures

3.5.1 Sense of Embodiment (SoE). We assessed SoE both in experience and post experience using the Virtual Embodiment Questionnaire (VEQ) [52]. The VEQ measures SoE on the three dimensions of perceived body ownership (BO), agency (AG), and change (CH), each with four items rated on a 7-pt Likert scale. For the in-experience assessment, we selected one item from each dimension, which loaded highest on it, and adapted the scales to range from 1 to 10. As we presented no virtual body in the reality condition, we adapted the wording of the items from "virtual body" to "visible body" for both assessments to match all of our conditions.

3.5.2 Self-Reported Body Awareness. We assessed self-reported body awareness ratings both in-experience and post-experience. For in-experience measurement, we extracted items from several questionnaires matching the following aspects of body awareness: noticing external cues (NE), noticing internal cues (NI), body listening (BL), attention regulation (AR), and visual attention (VA). The items were adapted from the State Mindfulness Scale (SMS) [62], the State Mindfulness Scale - Physical Activity (SMS-PA) [9], and the Objectified Body Consciousness Scale (OBCS) [47]. The extracted items, including sources, are presented in Table 1.

3.5.3 Interoceptive Accuracy (IAC). In addition to self-reported body awareness, we assessed IAC via a heartbeat-counting task [53]. Participants were instructed to sit calmly on a chair while resting their arms on the chair's armrest. They were asked to count their heartbeats over a trial of 45 sec but not guess if they did not feel any. To create an IAC score, we calculated the difference between their counting result and their actual heart rate during the time span relative to their actual heart rate.

3.5.4 Control Variables. To control potentially interfering factors, we additionally assessed the participants' everyday life body awareness using the Multidimensional Assessment of Interoceptive Awareness - Version 2 (MAIA) [44] questionnaire. It comprises 32 items divided into eight scales: noticing, non-distracting, not-worrying, attention regulation, emotional awareness, self-regulation, body listening, and trusting. It is measured on a 6-pt Likert scale ranging from 0 to 5. Additionally, we assessed the participants' everyday life body consciousness using the Objectified Body Consciousness Scale (OBCS) [47]. It comprises 16 items divided into two dimensions: body surveillance and body shame. It is measured on a 7-pt Likert scale ranging from 1 to 7. Finally, we controlled the VR-related variables simulator sickness and avatar uncanniness. To capture potentially occurring simulator sickness caused by latency jitter or other sources [59, 60], we included the Simulator Sickness Questionnaire (SSQ) [34]. It comprises 16 items, each querying a different symptom of simulator sickness, on a 4-pt scale ranging from 0 to 4. The total score ranges from 0 to 235.62. For avatar uncanniness, we assessed the Uncanny Valley Index (UVI) [31]. It comprises 18 items divided into four dimensions, humanness, eeriness, spine-tingling, and attractiveness. It is measured on a 7-pt scale ranging from 1 to 7. Additionally, we added two in-experience items for avatar uncanniness presented in Table 1.

3.6 Tasks

3.6.1 Body Awareness Movement Tasks. In both VR and reality, participants performed a series of movement exercises based on the Basic Body Awareness Therapy exercises from Gyllensten et al. [27]. These movement exercises usually aim to increase body awareness through small, repetitive body movements. The instructions focus on performing the movements slowly and deliberately while sensing the body. For our study, we selected only standing movement exercises. Following instructions for a stable, upright stance, participants performed the exercises "squat," "rotation," "wave," and "push" after each other for 75 to 115 seconds. For squat, participants performed a rocking motion of the legs to which they swung their arms. For rotation, they performed a rotation of the body around its longitudinal axis. Wave involved an up-and-down movement of the arms. For push, the subjects stood in step position and performed a forward press movement of the hands. For a more detailed description of each task, we refer to the work of Gyllensten et al. [27]. After the initial instruction of a movement task, we added the instruction to repeat the movement until the next exercise was presented. The pause between two instructions lasted 45 sec.

3.6.2 Mirror Exposure Task. Participants additionally performed a mirror exposure task. It established further exposure to the virtual body to test whether a confrontation with a virtual body in comparison to the physical body influenced body awareness. The mirror was turned around for the two conditions without a mirror to allow subjects to look at themselves for the first time during the study. In the other two conditions, the environment was not changed. Participants were instructed to stand centrally in front of the mirror and look at their mirror image for 3 min.

3.7 Procedure

The whole procedure of the study is illustrated in Figure 2. It was split into four phases: Preparation, reality condition, VR condition, and Closure. Both experimental conditions were presented in counterbalanced order and were executed with or without a mirror.

3.7.1 Preparation. During preparation, participants received information about the local COVID-19 regulation and the study procedure. They consented to the body scan and study participation and generated two personal pseudonymization codes to store their body scan and study data separately. Participants were then asked to take off their shoes. In the next step, the experimenter measured the participants' body height and performed the body scan described in Section 3.4.4. After the body scan, participants answered the pre-questionnaires, including their demographics, prior VR experience, and the MAIA, OBCS, and SSQ questionnaires. After answering the questionnaires, they performed the IAC task.

3.7.2 Reality Condition. In the reality condition, the participants were led to the center of the laboratory. Here, they performed the body awareness movement tasks described in Section 3.6.1. They then verbally answered the in-experience questions about body awareness, SoE, and avatar uncanniness. The mirror exposure task described in Section 3.6.2 followed. The instructions for both tasks were presented via pre-recorded audio instructions. The reality experience took M = 18.26 min (SD = 1.71). After the mirror exposure, the participants returned to the questionnaire workstation.

3.7.3 VR Condition. In preparation for the VR condition, the participants put on the tracking equipment described in Section 3.4.1. After introducing the virtual environment, participants were instructed to read a short sentence to test their vision within the virtual environment. The calibration of the virtual body followed. The participants were instructed to stand in a T-pose with their arms stretched to the sides. The instructions for the vision test and the calibration were presented verbally and in writing. A whiteboard to the left of the mirror displayed the written instructions. After calibration, the reality condition was performed analogously to the VR condition. The VR experience took M = 19.88 min (SD =1.86). After the last exercise, the participants put down the VR equipment and returned to the questionnaire workstation.

After each condition, the participants again performed the IAC task. Afterward, they answered the questionnaires SMS and VEQ. After the VR condition, they additionally answered the SSQ. At the end of the experiment, participants answered the UVI. In total, the study took M = 118.38 min (SD = 19.19).

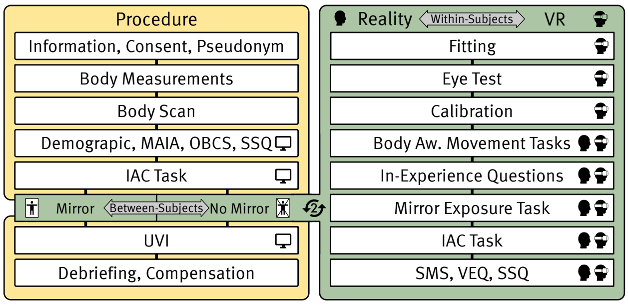

Figure 2: Overview of the experimental procedure (left) and of the repeated part of the exposure phase (right). The icons on each step's right side show the environment in which the step was conducted. The icon in the center indicates the repetition of steps.

4 RESULTS

4.1 Analysis

4.1.1 Effects of Virtuality and Perspective. We performed the entire analysis using R data analysis software. To analyze whether the virtuality or the perspective influenced the recorded measures of SoE and body awareness (H1.1, H1.2, H2.1, H2.2), we calculated 2×2 MANOVA models for the in-experience and 2×1 MANOVA models for the post-experience recorded measures of SoE and body awareness. For this purpose, we used the modified ANOVA-type statistic (MATS) for multivariate data proposed by Friedrich et al. [20], which is also applicable for repeated measures data. We applied the bootstrap approach proposed by Friedrich and Pauly [22] to avoid bias due to asymptotic distributions. To compute the model, we used the R package *MANOVA.RM* [21]. For the bootstrap, we applied 1000 iterations, each with parametric resampling. MANOVA models were interpreted at an alpha of .05.

For post-hoc comparisons after significant main effects, we directed 1×2 ANOVA models when only one main effect was significant or 2×2 ANOVA models when two main effects were significant. To account for small effects, we did not adjust the alpha value here. We calculated generalized η^2 (ges) as effect sizes.

4.1.2 Bayesian Multilayer Mediation. To analyze the extent to which the SoE towards the visible body mediated body awareness (H3), we considered the variables significantly affected by one of the two factors. We calculated a Bayesian multilayer mediation for each corresponding variable„ a multilevel modeling approach presented by Vuorre and Bolger [69], using their R package *bmlm.r.* Bayesian multilayer meditation takes non-independent observations from repeated measures into account and estimates regression models based on Markov Chain Monte Carlo (MCMC) procedures. These estimate individual-level and group-level parameters simultaneously. We used 2000 iterations for the sampling procedure. We report the means of the models' posterior distribution (Bayesian posterior distribution) and associated confidence intervals as estimates. In the results, we report the mediator models that showed a significant indirect effect based on confidence intervals and the respective direct effects.

4.1.3 Exploratory Analysis. In an additional exploratory analysis, we tested to what extent the participants found the encounter with their virtual bodies pleasant. For the in-experience measures of virtual body uncanniness, we calculated a 2×2 mixed design ANOVA model each. Again, we tested against an alpha level of .05.

4.2 Control Variables

4.2.1 Sample. Table 2 shows the results of all control variables for both the mirror and the no mirror group. To ensure that the two groups did not differ in their body awareness, we examined whether the MAIA was answered differently in the groups and whether performance in the IAC task differed.

4.2.2 General Effects of VR and Embodiment. We investigated the avatar's overall rating using the UVI. As shown in Table 2, the avatars were rated similarly between the mirror and no mirror condition on all dimensions. We found significant effects of virtuality on in-experience ratings of the visible body. Participants were more satisfied with their visible body in reality ($M = 7.97, SD = 1.70$) than in VR ($M = 6.30, SD = 2.21$), $F(1, 38) = 23.620, p < .001, ges = .157$. Additionally, participants felt more uncomfortable in their visible body in VR ($M = 3.17, SD = 2.24$) than in reality ($M = 2.30, SD = 1.47$), $F(1, 38) = 5.729, p = .022, ges = .052$. We found no significant effects of perspective on in-experience ratings of the visible body, neither for satisfaction, $F(1, 38) = 0.509, p = .480, ges = .009$, or for discomfort, $F(1, 38) = 0.131, p = .719, ges = .002$.

In a pre-post comparison of the SSQ scores, we tested whether participants had to be excluded due to simulator sickness. Results showed a maximum pre-post difference of 26.18 ($Md = -3.74, M = -7.67, SD = 19.75$) and a maximum post-measure of 104.72 ($Md = 18.70, M = 26.55, SD = 25.01$). As the participant with the highest increase in SSQ scores was not an outlier in the other scores and the two participants who scored maximum in post-measures reported only a small increase (11.22) or a decrease (−11.22) in SSQ scores, we referred from excluding participants due to simulation sickness.

Table 2: Descriptive results of all control variables divided between groups.

	Range	Mirror *M* (*SD*)	No mirror *M* (*SD*)
Body Awareness			
MAIA Attention regulation	[0 – 5]	4.11 (0.60)	4.21 (0.73)
MAIA Body listening	[0 – 5]	3.47 (1.05)	3.80 (0.79)
MAIA Emotional awareness	[0 – 5]	4.49 (0.94)	4.79 (0.67)
MAIA Self regulation	[0 – 5]	3.80 (1.01)	3.99 (0.79)
MAIA Non-distracting	[0 – 5]	1.03 (0.91)	0.92 (0.65)
MAIA Noticing	[0 – 5]	4.59 (0.77)	4.78 (0.51)
MAIA Not-worrying	[0 – 5]	2.44 (0.73)	2.29 (0.72)
MAIA Trusting	[0 – 5]	4.98 (0.85)	4.93 (0.86)
Interoceptive accuracy	[0 – 1]	0.65 (0.19)	0.66 (0.20)
Body Consciousness			
OBCS Body surveillance	[1 – 7]	3.79(0.50)	4.11 (0.64)
OBCS Body shame	[1 – 7]	3.00 (0.46)	2.69 (0.65)
Simulation Sickness	[0 – 220]	30.35 (4.12)	32.9 (5.25)
Avatar Uncanniness			
UVI Humanness	[1 – 7]	4.24 (1.40)	3.83 (1.25)
UVI Attractiveness	[1 – 7]	4.76 (1.00)	4.31 (1.19)
UVI Eeriness	[1 – 7]	4.11 (0.85)	4.45 (1.19)
UVI Spine-tingling	[1 – 7]	4.30 (0.83)	4.13 (0.87)
In-experience Satisfaction	[1 – 10]	6.95 (2.33)	7.32 (1.93)
In-experience Discomfort	[1 – 10]	2.83 (1.92)	2.65 (1.97)

4.3 Main Effects of Virtuality and Perspective

4.3.1 Sense of Embodiment. Table 3 shows the descriptive results of our dependent variables divided between the four conditions. In line with H1.1, our MANOVA model revealed a significant main effect of virtuality on SoE, $MATS = 120.623, p < .001$. Contrary to H1.2, it did neither reveal a significant main effect of the perspective on SoE, $MATS = 2.111, p = .521$, nor a significant interaction between virtuality and perspective, $MATS = 2.640, p = .416$. The post-hoc t-tests on virtuality revealed that when measured in-experience, perceived body ownership towards the visible body in reality was higher than in VR, $t(39) = 9.13, p < .001, d = 1.44$. Perceived agency towards the visible body was higher in reality than in VR, $t(39) = 7.80, p < .001, d = 1.23$. Perceived change of the physical body experience via the visible body was lower in reality than in VR, $t(39) = -2.93, p = .003, d = -0.46$. The result is depicted in Figure 3, left.

Confirming H1.1, when measured post-experience, our MANOVA model revealed a significant effect of virtuality on SoE, $MATS = 34.169, p < .001$. The post-hoc t-tests revealed when measured post-experience, perceived body ownership towards the visible body was higher in reality than in VR, $t(39) = 4.093, p < .001, d = 0.65$, perceived agency towards the visible body was higher in reality than in VR, $t(39) = 4.29, p < .001, ges = .679$. Perceived change of the physical body experience via the visible body was significantly higher in VR than in reality, $t(39) = -2.03, p = .025, d = -0.32$.

4.3.2 Body Awareness. When measured in-experience, in line with H2.1 and H2.2, our MANOVA model revealed a significant main effect of virtuality on body awareness ratings, $MATS = 14.174, p = 0.031$ and of the perspective on body awareness ratings, $MATS = 27.606, p = .002$. We did not find a significant interaction between virtuality and perspective, $MATS = 3.665, p = .577$. The post-hoc ANOVA models revealed some main effects of virtuality. When measured in-experience, noticing internal, $F(1, 38) = 7.485, p = .009, ges = .055$, attention regulation, $F(1, 38) = 4.662, p = .037, ges = .044$, and visual attention, $F(1, 38) = 4.763, p = .035, ges = .052$, were rated higher in reality than in VR, see Figure 3, right. For noticing external, $F(1, 38) = 2.22, p = .144, ges = .011$, and body listening, $F(1, 38) = 0.169, p = .683, ges = .002$, we did not find a significant impact of virtuality.

Similarly, post-hoc ANOVA models revealed some main effects for perspective. When measured in-experience, participants rated their visual attention higher when a mirror was available than when no mirror was available, $F(1, 38) = 24.255, p < .001, ges = .264$. We did not find a significant effect of the perspective on either noticing external, $F(1, 38) = 0.070, p = .793, ges = .001$, noticing internal, $F(1, 38) = 0.064, p = .802, ges = .001$, body listening, $F(1, 38) = 0.085, p = .773, ges = .002$, or attention regulation, $F(1, 38) = 0.051, p = .823, ges < .001$. Contrary to H2.1, we did not find a significant effect of virtuality on SMS Body ratings or IAC performance, $MATS = 1.737, p = .42$.

Table 3: Descriptive results of all variables compared between conditions.

		VR		Reality	
		Mirror	No mirror	Mirror	No mirror
	Range	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Sense of Embodiment (SoE)					
VEQ BO	[1 – 7]	4.82 (1.85)	4.65 (1.55)	6.26 (1.27)	5.95 (1.41)
VEQ Agency	[1 – 7]	5.76 (0.85)	5.66 (0.99)	6.61 (0.92)	6.36 (0.88)
VEQ Change	[1 – 7]	2.84 (1.70)	3.34 (1.48)	2.25 (1.28)	2.67 (1.72)
In-exp. BO	[1 – 10]	5.65 (2.56)	5.3 (2.30)	9.45 (1.32)	8.60 (1.76)
In-exp. Agency	[1 – 10]	6.00 (2.10)	6.4 (2.19)	9.60 (1.10)	8.75 (1.74)
In-exp. Change	[1 – 10]	5.30 (2.85)	5.4 (2.09)	3.55 (3.00)	3.80 (2.97)
Body Awareness					
SMS Body	[1 – 75]	3.67 (0.64)	3.60 (0.68)	3.82 (0.57)	3.67 (0.62)
Noticing External	[1 – 10]	4.55 (2.50)	4.00 (2.20)	4.65 (2.23)	4.85 (2.37)
Noticing Internal	[1 – 10]	7.10 (2.00)	7.35 (1.18)	8.15 (1.23)	7.70 (1.42)
Body Listening	[1 – 10]	6.70 (1.75)	6.90 (1.55)	7.15 (1.18)	7.20 (1.54)
Attention Regulation	[1 – 10]	6.80 (1.96)	7.25 (2.12)	8.10 (1.29)	7.45 (1.64)
Seeing vs. Feeling	[1 – 10]	6.40 (2.35)	3.70 (2.23)	5.25 (2.27)	2.85 (1.87)
Interoceptive Accuracy	[0 – 1]	0.66 (0.18)	0.69 (0.16)	0.70 (0.20)	0.73 (0.15)

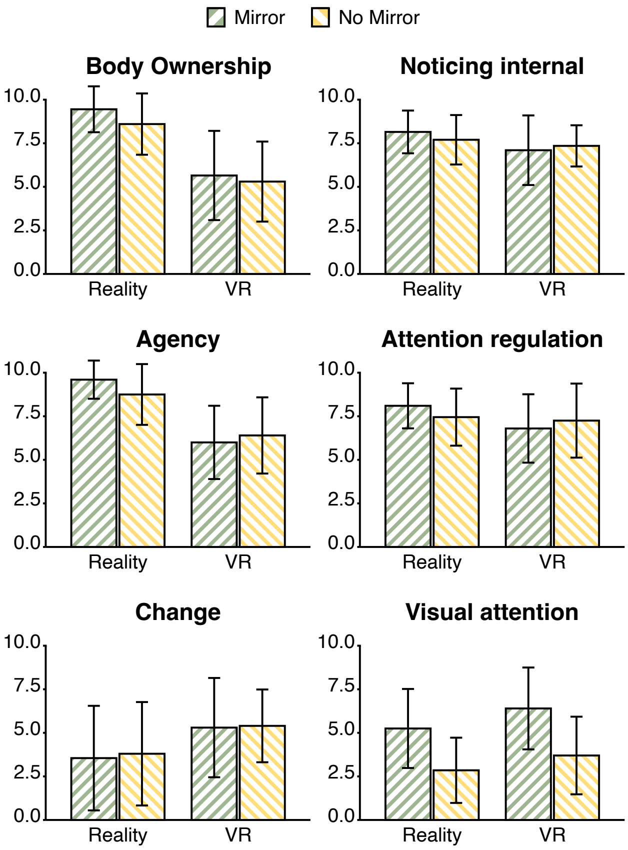

Figure 3: Means and standard deviations of body ownership, agency, and change (left) and noticing internal, attention regulation, and visual attention (right) in our conditions.

4.4 Mediator Analysis

Based on our main effects, we calculated a mediation analyses on virtuality as the independent variable, the three dimensions of SoE as mediator, and the body awareness ratings noticing internal, attention regulation, and visual attention as dependent variable.

4.4.1 Body Ownership. We tested whether body ownership mediated the effects between virtuality and in-experience body awareness ratings. We did not find a significant indirect effect between virtuality and body awareness through body ownership for noticing internal, $M_{posterior} = -0.14, SD = 0.19, CI = [-0.55, 0.18]$, attention regulation, $M_{posterior} = -0.13, SD = 0.15, CI = [-0.47, 0.12]$ or visual attention, $M_{posterior} = 0.06, SD = 0.13, CI = [-0.21, 0.35]$.

4.4.2 Agency. We tested whether agency served as a mediator between virtuality and body awareness ratings. We found no significant indirect effect between virtuality and body awareness through body ownership for noticing internal, $M_{posterior} = -0.18, SD = 0.16, CI = [-0.54, 0.09]$, or visual attention, $M_{posterior} = 0.08, SD = 0.13, CI = [-0.16, 0.38]$. However, we showed a significant indirect effect between virtuality and attention regulation through body ownership, $M_{posterior} = -0.26, SD = 0.17, CI = [-0.64, 0.00]$ (see Figure 4, left). As shown, virtuality predicted attention regulation (total effect), $M_{posterior} = -2.98, SD = 0.39, CI = [-3.72, -2.22]$, with users rating their attention regulation lower in VR than in reality. This effect was attenuated when controlling for agency (path c'), $M_{posterior} = -2.72, SD = 0.58, CI = [-3.45, -1.96]$. Virtuality further predicted agency (path a), $M_{posterior} = -0.76, SD = 0.63, CI = [-1.45, -0.08]$, with higher ratings of agency in reality than in VR. The feeling of agency was related to attention regulation (path b), $M_{posterior} = 0.34, SD = 0.06, CI = [0.06, 0.62]$.

4.4.3 Change. Finally, we tested whether change served as a mediator between virtuality and body awareness ratings. We encountered a significant indirect effect between virtuality and noticing internal through change, $M_{posterior} = 0.53, SD = 0.30, CI =$

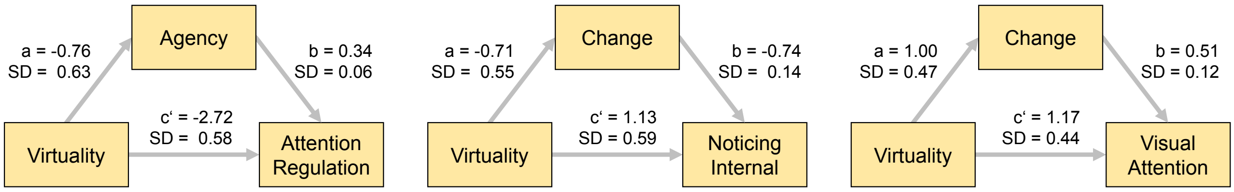

Figure 4: The left figure depicts the relative effect of virtuality on attention regulation and the two direct effects of virtuality on agency and of agency on attention regulation. The center figure depicts the relative effect of virtuality on noticing internal and the two direct effects of virtuality on change and of change on noticing internal. The right figure depicts the relative effect of virtuality on visual attention and the two direct effects of virtuality on change and of change on virtual attention.

$[0.06, 1.20]$, as depicted in Figure 4, center. As shown above, virtuality predicted noticing internal (total effect), $M_{posterior} = 1.66, SD = 0.56, CI = [0.59, 2.83]$, with users rating their noticing internal higher in VR than in reality. This effect was attenuated when controlling for change (path c'), $M_{posterior} = 1.13, SD = 0.59, CI = [0.04, 2.29]$. Again, as shown above, virtuality predicted change (path a), $M_{posterior} = -0.71, SD = 0.55, CI = [-1.21, -0.20]$, with higher ratings of change in VR than in reality. Additionally, the feeling of change was related to noticing internal (path b), $M_{posterior} = -0.74, SD = 0.14, CI = [-1.33, -0.13]$. Additionally, we found a significant indirect effect between virtuality and visual attention through change, $M_{posterior} = 0.51, SD = 0.29, CI = [0.02, 1.16]$, as depicted in Figure 4, right. As shown above, virtuality predicted visual attention (total effect), $M_{posterior} = 1.68, SD = 0.60, CI = [0.49, 2.83]$, with users rating their feeling higher in reality than in VR. This effect was attenuated when controlling for change (path c'), $M_{posterior} = 1.17, SD = 0.44, CI = [0.06, 2.24]$. Again, as shown above, virtuality predicted change, (path a), $M_{posterior} = 1.00, SD = 0.47, CI = [0.05, 1.95]$, with higher ratings of change in VR than in reality. Additionally, the feeling of change was related to visual attention (path b), $M_{posterior} = 0.51, SD = 0.12, CI = [0.23, 0.79]$. We did not find a significant indirect effect between virtuality and body awareness through change for attention regulation, $M_{posterior} = 0.51, SE = 0.29, CI = [0.02, 1.16]$.

5 DISCUSSION

In this paper, we presented a laboratory study on the effects of virtuality, perspective, and SoE on body awareness. We manipulated the degree of virtuality between plain reality and immersive VR to test whether self-reported body awareness and IAC during and after a body awareness task get affected. Additionally, we tested the effects of the visual perspective on the (virtual) body, operationalized via the presence or absence of a mirror. Mirrors provide a third-person perspective on the own body and are often used to enhance the SoE towards virtual bodies in VR. In contrast, body awareness tasks usually do not include mirror exposure. When answered in-experience, we found a significant negative effect of virtuality on body awareness ratings for noticing internal and attention regulation and a positive effect on visual attention. Further, we found a significant positive effect of the perspective on visual attention. Participants focused more on what they saw than what they felt when a mirror was present. In our study, feeling agency over a body and being changed by exposure to it mediated the effect of virtuality on body awareness. While agency partly explained the impact on attention regulation, change partly explained the effect on noticing internal and visual attention. However, these effects did not last until after the experience, as we did not find a significant impact of virtuality on either SMS ratings or heartbeat-counting performance (IAC). In the following, we discuss how these results answer whether the embodiment of virtual bodies is an opportunity or a threat to body awareness and virtual approaches to mind-body therapy.

5.1 Are Effects of a Mirror Perspective on Body Ownership a Myth?

As expected (H1.1), we found a significant effect of virtuality on the SoE. Both in-experience and post-experience, participants reported feeling more body ownership and agency towards their physical body in the real environment than towards their virtual body in VR. Additionally, they stated that they experienced more change in their bodily experience in VR than in reality. The ratings in the reality condition were generally very high for body ownership and agency. When assuming that all perception and cognition are body-based [72], the feeling of owning and controlling our physical body should be at a maximum at all times. However, some participants still rated their body ownership and agency in the reality condition lower than the maximum score and stated a feeling of change, although they did not have to split their body ownership between two competing bodies in this condition. There can be various reasons for this. There are certain states in which people do not feel embodied in their physical body or able to control it, such as depersonalization or derealization. The mere question of body ownership or agency may elicit a questioning of one's bodily state. Similar to the sense of presence in VR compared to reality [66], it seems to be possible that people generally do not report full SoE in reality. To what extent this should impact the interpretation of SoE ratings in virtual reality remains open for future work.

Contrary to our expectations (H1.2), our participants did not report different SoE when confronted with their mirror image than without it. Similar to our results, two recent studies investigated the effects of mirrors on the SoE. Wolf et al. [73] stepwise increased the distance to the third-person perspective provided by a virtual mirror from two to eight meters and could not find any sign of a declining SoE. Bartl et al. [6] investigated the effects of virtual bodies in VR-based physical exercises and did not find an effect of placing a virtual mirror in front of the participants. Past research shows that confrontation with (virtual) mirrors – while being used and proposed as a tool to reinforce SoE [11, 38, 57, 75] – has not yet been investigated extensively until recently. Studies on the impact of a third-person perspective on SoE often rely on a perspective where the participants see their virtual body only from behind, compared to an egocentric first-person perspective [11, 12, 26]. Apparently, both via first-person or third-person perspective, a certain amount of SoE can be achieved via visuomotor or visuotactile congruence. However, depending on the tracking accuracy, the first-person perspective, or alternating between both, lead to higher body ownership and agency than the third-person perspective [11].

Regarding our study, there are three possible explanations for the lack of perspective effects. First, our sample size was relatively small, and minor effects such as those visible in the descriptive data could have been detected with a larger sample. Second, our participants had potentially high expectations concerning the appearance and movements of their virtual bodies. To our knowledge, no research exists on the expectations of VR users toward their personalized virtual bodies. Thus, while Waltemate et al. [70] found a positive effect of personalization on SoE, minor deviations in facial features could have impacted the SoE in our study, especially as we did not contrast the personalized virtual bodies with generic virtual bodies. Future work should investigate whether the embodiment of generic or less realistic virtual bodies leads to similar results concerning the existence of a virtual mirror. Third, despite considerable technological progress, the embodiment of virtual bodies still does not work flawlessly. Contrary to the beneficial effect of mirrors in a virtual embodiment lab proposed by Spanlang et al. [57], in a study on the effect of mirrors on SoE, Rey et al. [51] found higher ratings in SoE in conditions without a mirror than in conditions with a mirror. They explained this effect based on the properties of the mirror they used. Inoue and Kitazaki [32] propose that SoE decreases during exposure to a virtual mirror image when the virtual body does not move synchronously. In our study, we used a low-threshold embodiment system with six-point tracking where the pose between points was calculated approximately. Thus, minor deviations in the posture of arms and legs and missing facial animations could have gradually reduced SoE over time. Consequently, more accurate tracking could be necessary to hold up SoE for such tasks. For future work, we recommend showing a mirror image only for a short introduction to the virtual body, if at all, to avoid possible disturbances caused by minor tracking deviations.

5.2 Virtuality Affects Body Awareness – Are Virtual Bodies Worth Considering in the Design of Mind-Body Therapy?

Using a realistic scenario and photorealistically personalized virtual bodies, we found some effects of virtuality on body awareness (H2.1) that did not last over the experience. During the experience, our participants found it significantly more challenging to focus on their bodies, reported noticing fewer signals from within their bodies, and relied more on what they saw than what they felt in VR than in reality. Filippetti and Tsakiris [19] reported a positive effect of the RHI on body awareness, operationalized as IAC. We could not extend this result to virtual bodies in our study, as we did not find an effect of virtuality on IAC. Our effects on self-reported body awareness indicate a negative impact of virtuality.

Since we did not work with generic body parts in our setup but with personalized virtual bodies, our results are more comparable to the second experiment of Filippetti and Tsakiris [19]. They showed that prolonged confrontation with images of one's face in an enfacement illusion could harm IAC. While IAC and self-reported body awareness are discussed as independent concepts [18], our results on self-reported body awareness indicate a similar effect of the confrontation with photorealistically personalized virtual bodies on body awareness. Still, we did not find an effect of virtuality on IAC. In our study, the use of a mirror without additional haptic stimulation or the inclusion of facial animations had close to no effect. This result contradicts the hypothesis that the confrontation with one's face would be a causal factor in differences in body awareness (H2.2). While participants reported that they paid more attention to their visuals than to their other bodily sensations, they did not report reduced body awareness in the other measures. Future work could investigate how the personalization of virtual bodies contributes to the found effects. In previous work, personalization has affected SoE positively [70] and IAC negatively [19]. However, the extent to which it affects body awareness when embodying a virtual body has not yet been investigated. In addition, future work should address to what extent not only latency but posture accuracy and tracking performance [23] affect body awareness. Previous studies mainly focused on the effects of visuotactile congruence, while no transfer to virtual bodies and visuomotor congruence has been performed yet. It may be concluded that virtuality, at least for our realistic scenario, had neither a lasting supportive nor a disruptive effect on body awareness. Further, providing a mirror to supposedly strengthen the SoE did not affect body awareness negatively. To ensure that the focus during a virtual mind-body exercise remains on the body's sensations, and as the positive effect of prolonged mirror exposure on SoE is questionable, we would still argue against using a mirror during the whole length of virtual exercises.

Future research will bring further insights into how virtual body design can support users in maintaining body awareness. Although we found only a partial impact of VR on body awareness, caution should be exercised when using virtual bodies in VR-based mind-body exercises. When creating such scenarios, designers should consider how the VR environment, the performed task, and the virtual body itself affect body awareness. For example, if a mirror is task-immanent, designers should identify solutions to draw attention back to internal body signals. When an avatar is used to guide the user, its appearance and behavior should aim to draw attention to the body while avoiding visual distractions. Depending on the intended outcome, designers should carefully consider to what extent a distraction from internal body signals is likely to happen, problematic, or even desirable.

5.3 SoE Mediates the Effects of Virtuality on Body Awareness

Based on the work of Filippetti and Tsakiris [19] and Döllinger et al. [15], we expected that a manipulation of the SoE would mediate the perceived body awareness in our tasks (H3). Our results partly confirmed this assumption as we found significant mediating effects of SoE on each of the variables that were affected by virtuality. We found a significant partial mediating effect of perceived agency on attention regulation and a significant partial mediating effect of perceived change on noticing internal and visual attention. While a higher agency was associated with a higher attention regulation, higher change ratings were associated with less noticing internal and more attention to visual signals. However, we did not find mediating effects for the effect of perspective on body awareness. The result is consistent with Döllinger et al. [15], who found a positive correlation between body ownership and agency and body awareness (assessed via SMS). However, it extends the findings as we could show that not only was SoE related to body awareness ratings but also explained part of the effects of virtuality on body awareness. The negative correlation between change and noticing internal is particularly interesting. When embodying virtual bodies, we are confronted with potentially contradicting signals about our bodies. If these lead us to perceive our body as changed, the visual signals seem to have more influence than the internal signals. This result thus fits well with the assumptions of research on individual differences in SoE towards a rubber hand or virtual body [13, 54, 63, 64]. It supports the hypothesis that external and internal stimuli compete in such scenarios. While prior work focused on individual capacity to process external signals, we showed that, at least in the short term, increased processing of external stimuli appears to be associated with reduced processing of internal stimuli.

5.4 Limitations

In addition to the limitations already mentioned above, such as the sample size or possible tracking imprecision, we would like to mention a few limitations of our study design. Our results are limited to virtual experiences where the virtual environment and the virtual body of the participants strongly resemble reality. In developing the virtual environment, we replicated the local laboratory as closely as possible and created personalized photorealistic virtual replicas of the participants. This level of realism and personalization is not feasible in most cases. Work on virtually supported mind-body interventions presents very heterogeneous virtual environments and virtual bodies that are adapted to the goal of the task rather than to the user or do not include virtual bodies at all [14]. To generalize our results, it is necessary to replicate them in diverse virtual spaces, with less personalized or generic virtual bodies, or even without an anthropomorphic self-representation. We can only conclude that even in a scenario like ours, a negative influence of the embodiment of virtual bodies on body awareness cannot be excluded completely. In addition to the degree of realism, our choice of tasks also limits our results. The subjects in our study performed tasks designed to increase body awareness specifically. Since we focused on the application context of mind-body therapies, we initially limited our task selection. However, it remains to be investigated whether a more substantial effect on body awareness has to be expected in other tasks that are less movement- or body-focused. For further application, it would be vital to conduct investigations on body awareness in different virtual scenarios. Finally, our design is limited because a mirror exposure was performed at the end of each condition to highlight the difference between virtuality and reality more clearly. However, it limits the results on the influence of perspective to the extent that the post-experience surveys could not be investigated concerning perspective.

6 CONCLUSION

Virtual reality (VR) allows for replacing the visual information about our body with an arbitrary virtual self-representation (virtual body). In our study, we showed how embodying a photorealistically personalized virtual body affects the awareness of one's internal body signals (body awareness) and how the sense of embodiment is involved in the effects of virtuality and perspective on body awareness. Our results reveal that individuals perceive a lower sense of embodiment towards their virtual body in a virtual scenario than towards their real body in reality. They further indicate that individuals are slightly less aware of their internal body signals during the embodiment of a virtual body than in reality. A method often used to increase the sense of embodiment, a virtual mirror, did not positively affect the sense of embodiment in our study but caused individuals to focus more on their appearance than on their internal body signals. Finally, we could show that the sense of embodiment, and especially the feeling of being physically changed during an experience, mediates the effects of VR on body awareness. Future work should investigate whether the effects we found also appear with less personalized or generic virtual bodies in diverse virtual experiences. It should further investigate whether they also occur in different tasks that are not dedicated to body movement or body awareness.

ACKNOWLEDGMENTS

This research has been funded by the German Federal Ministry of Education and Research in the project ViTraS (16SV8219 and 16SV8225) and by the Bavarian State Ministry for Digital Affairs in the project XR Hub (A5-3822-2-16). We thank Roland Zechner for his support with our illustrations. Erik Wolf gratefully acknowledges a Meta Research PhD Fellowship.

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5 If It's Not Me It Doesn't Make a Difference – The Impact of Avatar Personalization on User Experience and Body Awareness in Virtual Reality

Döllinger, N., Beck, M., Wolf, E., Mal, D., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023). "If it's not me it doesn't make a difference" – the impact of avatar personalization on user experience and body awareness in virtual reality. *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 483–492. doi: 10.1109/ISMAR59233.2023.00063

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Author Contributions

Nina Döllinger conceptualized the experimental design, supervised data collection, performed the analysis, and took the lead in writing the manuscript. Matthias Beck supported adapted the Unity application for the experiment, created the generic avatars and the avatar-selector, and collected data. Erik Wolf and David Mal developed the Unity application including the experimental environment and avatar animation system. Mario Botsch provided the avatar reconstruction framework. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)

"If It's Not Me It Doesn't Make a Difference" – The Impact of Avatar Personalization on User Experience and Body Awareness in Virtual Reality

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2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) | 979-8-3503-2838-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/ISMAR59233.2023.00063

Figure 1: Example of two study conditions using customized avatars (left) or personalized avatars (right).

Abstract

Body awareness is relevant for the efficacy of psychotherapy. However, previous work on virtual reality (VR) and avatar-assisted therapy has often overlooked it. We investigated the effect of avatar individualization on body awareness in the context of VR-specific user experience, including sense of embodiment (SoE), plausibility, and sense of presence (SoP). In a between-subject design, 86 participants embodied three avatar types and engaged in VR movement exercises. The avatars were (1) generic and gender-matched, (2) customized from a set of pre-existing options, or (3) personalized photorealistic scans. Compared to the other conditions, participants with personalized avatars reported increased SoE, yet higher eeriness and reduced body awareness. Further, SoE and SoP positively correlated with body awareness across conditions. Our results indicate that VR user experience and body awareness do not always dovetail and do not necessarily predict each other. Future research should work towards a balance between body awareness and SoE.

Keywords: Virtual reality, embodiment, personalization, body awareness, virtual body ownership, avatars, user experience.

Index Terms: Human-centered computing—Empirical studies in HCI; Virtual reality; Usability testing;

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1 Introduction

Virtual reality (VR) is a powerful tool for presenting novel environments and unique bodily experiences to users. It can trigger physical fear responses [25], induce a change in body weight perception [55, 81], or create compelling new worlds that respond flexibly to the user's bio-signals [43]. Thus, VR offers possibilities beyond reality. It has been considered for years to support therapy. Initially, the main focus of therapeutic VR applications has been on phobias or addiction. However, there is a growing interest in mind-body interventions, which aim to improve mental health by addressing the connection between bodily experiences and well-being. In recent years, numerous VR applications have emerged specifically designed to enhance mindfulness, body awareness, and overall mental health.

Research on VR in mind-body interventions mainly focuses on therapeutic targets, while effects on users' mindfulness are rarely addressed [19]. Especially body awareness, a part of mindfulness closely related to well-being that contributes to mind-body interventions' success, has yet to be targeted sufficiently [3]. It has yet to be addressed how mindfulness and body awareness are affected by and how they reiterate the more general user experience in VR (VR UX). This includes, for example, the sense of presence (SoP) in a virtual environment, or the sense of embodiment (SoE) towards one's virtual body [19]. Moreover, little has been investigated regarding the use of virtual avatars and their visual appearance in this therapeutic field. In other research fields, avatar appearance, especially the similarity between a user and their avatar, has been shown to impact the user's SoE [78] or their health behavior [59]. However, there is still a lack of connecting the SoE and other VR UX measures with the respective target behaviors [59, 79] or underlying experiences, such as body awareness.

To address these gaps, we present a study focusing on how body awareness, as a body-centered aspect of mindfulness and as an underlying structure in mind-body therapies, relates to virtual body

DOI 10.1109/ISMAR59233.2023.00063

appearance and common VR UX measures. The work draws on substantial prior work on photorealistic personalized avatars. It investigates whether the degree of avatar individualization affects body awareness, avatar-related UX, and, more generally, VR UX. Based on the BehaveFIT framework by Wienrich et al. [79], we investigate the following research questions:

1. Does the degree of individualization of an embodied avatar impact body awareness and VR UX in a VR mind-body exercise?
2. Does VR UX affect body awareness?
3. Does the degree of avatar individualization impact the relationship between VR UX and body awareness?

Participants embodied a generic realistic same-gender avatar, a customized avatar using a custom avatar selection system, or apersonalized, photorealistic scan avatar. In VR, they perform repetitive movements from Basic Body Awareness Therapy [30]. We assessed body awareness, mindfulness, and various avatar-related and avatar-unrelated VR UX measures. The paper contributes to the understanding of avatar embodiment for therapy by demonstrating the extent to which realistic low-cost customized avatars affect body awareness in a virtual environment compared to photorealistically personalized avatars. In therapeutic settings, maximum personalization of avatars is not always possible. We contribute to determining the trade-off between avatar design and possible consequences for body awareness. Further, we place body awareness in a VR exercise in the context of standard VR UX measures, including SoE and SoP.

2 Related Work

According to the theory of embodied cognition, all thoughts and feelings arise from physical experiences. While our body allows us to connect, perceive, and interact with our environment, the perception of our body itself is also an essential and multifaceted component of our experience. Body awareness, the attention we pay to the perception of our body, often summarized as interoception or paired with proprioception, is an object of observation that has aroused broad interest over the years. Especially attention to the inside of the body has been associated with several psychosomatic benefits. It is operationalized via interoceptive accuracy, the ability to feel one's heartbeat [62], or via subjective self-assessment to notice, be aware of, regulate and trust body perceptions [47]. High body awareness is negatively related to depression and anxiety [18], pain and fatigue [27, 64], suicidality [32], or eating disorder symptoms [9]. Mind-body therapy success, attributed initially to mindfulness, is increasingly attributed to body awareness as a core impact [28].

2.1 The Transbodily Experience of Embodying an Avatar

The experience of simultaneously having and being a body has been the topic of numerous research [34, 56]. Various studies have investigated how we experience embodiment not only towards our natural body but also to artificial objects, such as in the Rubber Hand Illusion [71], or toward virtual bodies, avatars, in VR [52], delving into their impact on behaviors and therapeutic outcomes. The feeling we experience towards an avatar has been described as a virtual SoE [38]. To what extent such SoE equals the experience of being and having a physical body remains unclear. Being a body implies perceiving and interacting with the environment [77]. Being a virtual body would thus translate into the avatar allowing us to perceive the virtual environment. This statement does not hold, as in VR, our physical body still is the source of our perceptions and actions. However, our virtual body can induce a sense of agency [38, 60].

Embodiment further includes having a body, a perceivable physical entity representing us in an environment [77]. This concept translates more directly into the embodiment of avatars. Aligning the avatar as a virtual object and self-representation in VR with the natural body is pivotal for the SoE. The avatar's appearance, including gender, race, and realism, is decisive for this alignment. Depending on the appearance and behavior of the avatar, having a virtual body can elicit a sense of virtual body ownership (VBO) [38].

The embodiment of avatars extends the perception of simultaneously having and being a body to simultaneously having a set of bodies while still being one. VR offers the possibility of visually replacing, enriching or superimposing the physical body at will with the targeted representation of a virtual body. Body movement tracking systems allow the virtual body to follow the user's physical movements precisely and elicit a feeling of agency over the virtual body, which mixes in with the sense of VBO [38, 60]. As the visual perception of the virtual body integrates with the perception of the physical body, the focus of attention shifts toward the visible body, and the perception of actual body posture [75], movement speed or direction [36], body size [39, 81], or visual appearance [54, 57] recedes into the background. It is unclear to what extent users experience the virtual body as a part, extension, or substitute of the physical body or to what extent the perception of the virtual body contributes to a sense of change in the physical body [60]. Nevertheless, this transbodily experience's impact can be enriching and devastating to the users' self-perception [5, 17].

2.2 Sense of Embodiment and Body Awareness

For the usage of VR and avatars in mind-body therapy, it is essential to investigate how the embodiment of avatars is related to our physical body awareness. Previous research on this encounter has led to mixed results. A person's body awareness trait can affect how susceptible they are to accept artificial body parts or virtual bodies [24, 50, 63, 68, 69] and how susceptible they are to be influenced in their interoceptive accuracy by congruent or incongruent stimulation [24]. These effects might result from an increased susceptibility to external stimuli in participants with low awareness of internal body signals. Studies on self-reported trait body awareness scales and SoE yielded mixed results [10, 13, 15]. However, a self-reported state of body awareness positively correlates to VBO and agency using personalized, photorealistic avatars [20]. Döllinger et al. [17] compared body awareness in VR to a real mirror exposure. In their study, VR negatively impacted self-reported body awareness, indicating a shift of attention toward visual processing. A sense of being physically changed by the avatar mediated this effect.

A majority of the studies on SoE and body awareness focus on the Rubber Hand Illusion [13, 24, 63] or faces presented as images and embodied via visuotactile stimulation [24]. Others use fully embodied generic-looking [15] or elaborately created photorealistic avatars [17, 20]. The results diverge accordingly. It has yet to be investigated systematically how the appearance of a full-body avatar impacts the relationship between SoE and body awareness.

2.3 The Impact of Avatar Appearance

Numerous studies have delved into the impact of avatar appearance on SoE. One example is the degree of anthropomorphism of the avatar. Mixed results have been observed so far. In earlier studies, the less human-looking or less realistic avatars increased VBO [35, 44, 46]. In later studies, this effect was inverted [40]. Besides a realistic human appearance of the avatars, the similarity between user and avatar contributes to a SoE. For instance, Jo et al. [35] found that individualizing avatars had a greater effect on VBO than increasing rendering realism. Similarly, Waltemate et al. [76] demonstrated that personalization positively affected VBO using photorealistic scanned avatars. In contrast, the degree of realism had no effect when comparing scanned to hand-modeled generic avatars. Salagean et al. [61] investigated the impact of personalization and photorealism using lower and higher photorealistic avatars. They found a significant in-VR effect on VBO, indicating a higher VBO for highly photorealistic, personalized avatars. Matching the results of former studies, they found an overall positive effect of photorealism and personalization on VBO. These results are consistent with two recent reviews. Weidner et al. [78] analyzed the effects of avatar and virtual body part appearance on different aspects of VR perception, especially the SoE. They found that the VBO benefits from a personalized avatar appearance, independently from the degree of realism. They concluded that generic realistic or personalized realistic full-body self-avatars could be promising but emphasized the need to explore varying realistic appearances. The results of Mottelsson et al. [52] support this conclusion. A systematic meta-analysis found that avatar individualization affected VBO and, to a limited degree, the sense of agency. However, they found these effects in only a limited number of papers. Accordingly, they, too, stress the importance of further investigation.

2.4 The Role of VR User Experience

In addition to investigating SoE, several avatar-related and non-avatar-related variables are open to debate in research on VR experiences. The most commonly mentioned VR UX variable is the SoP, which has been discussed, analyzed, and investigated for underlying perceptual mechanisms such as plausibility in various works [41, 66, 67]. In the area of avatar and agent evaluation, in addition to SoE, variables such as virtual human plausibility, i.e., the perception of the plausibility of the appearance and behavior of an avatar in VR, are discussed [45]. In addition, the uncanny valley effect is considered widely. It describes a feeling of eeriness towards realistic, human-like avatars [16]. This effect should be controlled for the usage of VR in a therapeutic setting and has been named as an exclusion criterion for the use of avatars [65]. To better understand the psychological mechanisms of VR in therapy, Wienrich et al. [79] suggest that any investigation of VR interventions should go beyond assessing the VR's effect on the respective behavioral or therapeutic outcome. They suggest considering moderator or mediator effects of VR UX variables and their association with therapeutically relevant psychological states. However, previous work on VR-induced health behaviors [59] or VR mind-body interventions [19] has rarely considered the relationship between intended behaviors or psychological states and VR UX. Regarding mind-body interventions, first experiments have investigated the relationship between SoE and body awareness. However, how body awareness behaves in relation to other VR UX measures remains open.

3 Methods

3.1 Design

In a 3×1 study design, participants were randomly assigned to one of three conditions with different levels of avatar individualization (see Fig. 2). In the first condition, *generic*, participants embodied a generic, realistic-looking humanoid avatar. In the second condition, *customized*, the participants chose the appearance of their realistic-looking humanoid avatar using a custom avatar selection system (see Section 3.3.3). In the third condition, *personalized*, the participants embodied photorealistic scans of their real bodies. As dependent variables, we tested the participant's body awareness, interoceptive accuracy, and avatar-related and non-avatar-related measures of VR UX. The study was conducted according to the Declaration of Helsinki and approved by the ethics committee of the Institute Human-Computer-Media (MCM) of the University of Würzburg [1].

3.2 Participants

Ninety-four individuals participated in the study and received course credits or 15 EUR. We excluded individuals (1) with photosensitivity (e.g., due to epilepsy), (2) with severe uncompensated visual impairments, (3) with mobility difficulties, (4) when reporting symptoms of simulation sickness, or (5) with less than three years of experience with the German language. We included two control items asking to mark a specific rating. We excluded one participant due to not marking asked ratings. Further, we excluded three participants due to tracking/calibration errors and four due to errors in constructing the personalized avatar. A total of 86 participants remained. In the generic condition, $n = 29$, the mean age was $M = 23.10$ years ($SD = 3.88$), with 23 female and six male participants. Seventeen had < 5 hr, eight had $5 - 20$ hr, and four had > 20 hr of VR experience. In the customized condition, $n = 29$, the mean age was $M = 25.03$ years ($SD = 7.64$), with 19 female and ten male participants. Thirteen had < 5 hr, eight had $5 - 20$ hr, and seven had > 20 hr of VR experience. In the personalized condition, $n = 28$, the mean age was $M = 21.54$ years ($SD = 2.40$), with 23 female and five male participants. Twenty had < 5 hr, three had $5 - 20$ hr, and six had > 20 hr of VR experience.

3.3 Apparatus

The study was performed in a quiet laboratory at the University of Würzburg, Germany. It consisted of a small office room, where participants could answer questionnaires on a desktop computer using LimeSurvey 4 [42], and a bigger lab room for the VR exposition.

3.3.1 Technical System

The VR system consisted of a Valve Index Head-Mounted Display (HMD) [74] and two Valve Index controllers (Knuckles) tracked by three SteamVR Base Stations 2.0. The cable-bound HMD provided a resolution of 1440×1600 px per eye, a refresh rate of 144 Hz, and a total field of view of $109.4 \times 114.1^\circ$ [80]. It was driven by a high-end gaming PC with an Intel Core i7-9700K, an Nvidia RTX2080 TI, and 32 GB RAM running Windows 10. The participants' fingers were tracked via the proximity sensors of the Knuckles. We did not include tracking of facial expressions. For body tracking, we used the markerless tracking system from Captury [8], employing eight FLIR Blackfly S BFS-PGE-16S2C RGB cameras attached to the laboratory ceiling to track participants' movements at a rate of 100 Hz. The cameras were connected to a powerful workstation composed of an Intel Core i7-9700K, an Nvidia RTX2080 TI, 32 GB RAM, and two 4-port 1 GBit/s ethernet frame-grabber running Ubuntu 18 and Captury Live (version 248). We captured the participant's heart rate using the Empatica E4 smartwatch [22] connected via Bluetooth to a Samsung Galaxy S6 smartphone for data logging. The VR experience was implemented using Unity (version 2020.3.25f1 LTS) [73] and integrated the VR system using SteamVR and its corresponding Unity plug-in (version 2.6.1)[2]. The body pose was continuously streamed to the VR system using a 1 GBit/s ethernet connection and integrated using Captury's Unity plug-in[3]. Subsequently, we always retargeted the received body pose to the currently used avatar. We merged it with the remaining tracking data from the VR system using Unity's avatar animation system and a custom-written retargeting script using the implementations utilized in our prior works [20, 21].

3.3.2 Virtual Environment

Participants were exposed to a virtual office adapted from a Unity asset[4] that included a couch, a desk, a mirror, and a large window showing a wood-inspired environment (see Fig. 1). Following the guidelines for mirror placement by Wolf et al. [80], the participants' position was determined by rendering a position marker on the floor at a distance of 1.5 m in front of the mirror. Left to the mirror, we added a whiteboard to display experimental instructions. The walls of the virtual room were aligned roughly according to the walls of the lab, creating an intuitive limit for the possible movement area.

3.3.3 Avatars

Generic For the generic condition, we created one female and one male avatar using the Autodesk Avatar Generator (version

[1]https://www.mcm.uni-wuerzburg.de/forschung/ethikkommission/

[2]https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

[3]https://captury.com/resources/

[4]https://assetstore.unity.com/packages/3d/props/interior/manager-office-interior-107709

Figure 2: Generic (left), customized (center), and personalized (right) avatar of an exemplary participant.

1.0.693) [4]. We exported them as a quad mesh with high resolution for Unity. Fig. 2, left, shows the generic male avatar. The female version was designed accordingly.

Customized For the customized condition (Fig. 2, center), we chose six body characteristics and varied them systematically, resulting in 67 avatars created using the Autodesk Avatar Generator. The characteristics included a variation in gender (male and female), skin color (light-skinned and dark-skinned), body shape (low body fat, high body fat, and high muscle mass), clothing (black and white shirt), hair color (brown and blonde), and hair length (short and long). To allow user customization, we created an avatar selector as part of the LimeSurvey questionnaires. Step by step, participants were presented with a subset of the avatars and asked to select the avatar that best matched their appearance. The selection started with the gender and skin color of the avatar, moving on to the body shape and proceeding to the hair length, color, and clothing.

Personalized For the personalized condition, we created photorealistic avatars of our participants (see Fig. 1, right or Fig. 2, right) using the reconstruction pipeline presented by Achenbach et al. [1]. The generation process followed the procedure described by Bartl et al. [6] and involved capturing 94 simultaneous photos of the participants using a custom-built multi-DSLR camera setup. The photos were input for generating a dense point cloud representation of the participants' bodies using Agisoft Metashape [2]. The point cloud was the foundation for modifying a fully rigged template mesh sourced from the Autodesk Character Generator [4] based on statistical parameters and non-rigid deformation. Finally, we created the avatar's photorealistically personalized texture [6].

3.4 Measures

3.4.1 Body Awareness and Mindfulness

We assessed several aspects of body awareness using rating scales and performance measures. We assessed the participants' everyday life body awareness using the Multidimensional Assessment of Interoceptive Awareness - Version 2 (MAIA) [47] questionnaire. It comprises 37 items divided into eight scales: Noticing, Non-Distracting, Not-Worrying, Attention Regulation, Emotional Awareness, Self-Eegulation, Body Listening, and Trusting. It is measured on a 6-pt Likert scale ranging from 0 to 5.

We used the State Mindfulness Scale (SMS) [70] to assess body awareness post-VR. It consists of 21 items divided into two scales: state mindfulness of mind (SMS Mind, 15 items) and state mindfulness of body (SMS Body, 6 items). It is measured on a 5-pt Likert scale ranging from 1 to 5.

To assess body awareness in VR, we extracted items from several questionnaires matching the following aspects: Noticing External, Noticing Internal, Body Listening, Attention Regulation, and Visual Attention [17]. The items were adapted from the SMS, the State Mindfulness Scale - Physical Activity (SMS-PA) [12], and the Objectified Body Consciousness Scale (OBCS) [51]. To separate body awareness from mindfulness, we created three additional in-VR items for mindfulness, assessing the Noticing of Thoughts, the Noticing of Affect, and Thought Watching. All of these were extracted from the SMS [70]. The in-VR items were presented as 10-pt scales ranging from 1 to 10.

In addition, we assessed interoceptive accuracy via a heartbeat-counting task (HCT) [62] using the instructions presented by Desmedt et al. [14]. Participants sat on a chair while resting their arms on the armrest. We instructed them to count their heartbeats over a trial of 45 sec. We calculated an interoceptive accuracy score by dividing the absolute difference between counted and actual heartbeats by the actual heartbeats, resulting in a percentual score between 0 and 1, with higher numbers indicating higher interoceptive accuracy. As we had some technical issues during heartbeat tracking, the results on HCT are reduced to N = 77 participants (n = 27 generic, n = 27 customized, n = 23 personalized).

3.4.2 VR UX: Avatar Perception

Regarding avatar-related VR UX, we assessed the following variables: SoE, virtual human plausibility, and the uncanny valley effect.

We assessed SoE in VR and post VR using the Virtual Embodiment Questionnaire (VEQ) [60]. The VEQ assesses SoE on the three dimensions of perceived Body Ownership (BO), Agency (AG), and Change (CH), each with four items rated on a 7-pt Likert scale. For in-VR assessment, we selected one item from each dimension, inVR BO, inVR AG, and inVR CH, which loaded highest on it and adapted the scales to range from 1 to 10.

To assess virtual human plausibility, we used the Virtual Human Plausibility Scale (VHPS) [45]. The VHPS consists of 11 items presented as 7-pt Likert scales, ranging from 1 to 7. It includes two dimensions, virtual human Appearance and Behavior Plausibility (ABP) and virtual human Match to the Virtual Environment (MVE).

We used the Uncanny Valley Index (UVI) [33] to assess the uncanny valley effect. It comprises an affective appraisal of the avatar using 18 items divided into three dimensions, Humanness, Eeriness, and Attractiveness. It is measured on a 7-pt scale ranging from 1 to 7. Additionally, we included two in-VR items that matched the UVI: inVR Satisfaction and inVR Discomfort [17].

3.4.3 VR UX: Non-Avatar-Related Measures

Finally, we controlled non-avatar-related VR UX variables, SoP, and simulator sickness. To assess SoP, we used the in-VR One Item Presence Scale (OIPS) [7]. It consists of a single item, using a 10-pt scale ranging from 1 to 10. To capture simulator sickness, we included the Simulator Sickness Questionnaire (SSQ) [37]. It includes 16 items and three dimensions, Nausea, Oculomotor, and Disorientation. Items are assessed on a 5-pt scale ranging from 0 to 4. The total score ranges from 0 to 220.

3.5 Tasks and Procedure

3.5.1 Embodiment Tasks

To evoke an SoE, the participants performed movement tasks based on Waltemate et al. [76]. The exercises target different body parts and have a duration of about 20 s each, slightly differing by the length of the instruction. Guided by audio instructions, participants waved at their reflection, lifted their knees, and rotated their hips while raising their arms. The embodiment tasks lasted 3 min and 4 s.

3.5.2 Body Awareness Movement Tasks

The leading VR task consisted of standing movement tasks based on the Basic Body Awareness Therapy exercises [30]. These aim to evoke body awareness through repetitive, small-scale body movements. The instructions emphasized performing the movements slowly and attentively, focusing on sensing the body during the process. Following instructions for maintaining a stable and upright

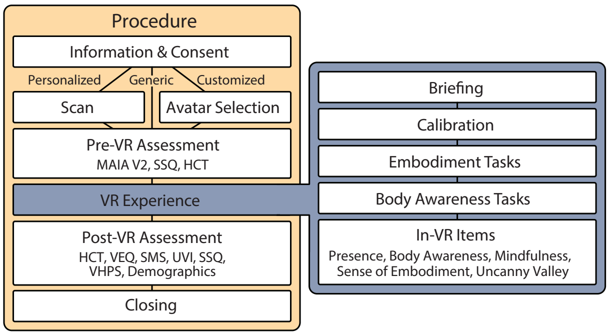

Figure 3: Overview of the experimental procedure.

stance, participants sequentially performed the exercises ‘squat,” “rotation,” “wave,” and “push” for durations ranging from 75 to 115 s each. The squat exercise involved a rocking motion of the legs accompanied by arm swinging. In the rotation exercise, participants rotated their torsos from left to right. The wave exercise comprised an up-and-down movement of the arms. Lastly, participants adopted a step position and executed a forward-pushing movement with their hands. After providing the initial instruction for a movement task, we instructed the participants to repeat the movement until the next instruction. The interval between instructions lasted 45 s. The body awareness movement tasks lasted 13 min and 19 s.

3.5.3 Procedure

Fig. 3 shows the whole experimental procedure. It consisted of three phases: pre-VR, in-VR, and post-VR. Pre-VR, all participants started by reading the study information and signing consent to participation and data processing. Participants in the customized conditions started customizing their avatar, while participants in the personalized condition underwent the body scan process. In the next step, all participants answered the MAIA and SSQ questionnaires and assessed their interoceptive accuracy via HCT.

In-VR, the participants received a short briefing and were introduced to the VR equipment and virtual environment. The VR experience followed a set sequence along with pre-recorded audio instructions. First, users tested their vision. We calibrated the body tracking system and adjusted the avatars’ to the participants’ body height. For calibration, participants had to perform a few idle movements and then stand motionless, looking straight ahead. In this phase, all instructions were additionally presented on the virtual whiteboard to ensure a rigorous execution and optimal calibration. Next, the whiteboard disappeared, and the avatar and a virtual mirror appeared. The participants were instructed to look at their avatar and perform the embodiment tasks in front of the mirror (see Sect. 3.5.1). The mirror disappeared, and participants performed the body awareness movement tasks (see Sect. 3.5.2). Finally, the virtual whiteboard reappeared. The in-VR items were presented visually and auditory. Participants were instructed to express the answer to each question aloud. To reduce social desirability bias, we emphasized that all answers were valid and no wrong answers could be given. Answering questions lasted about three minutes. The participants spent $M = 22.24$ ($SD = 0.96$) min in VR. Post-VR, the participants performed the HCT a second time. Finally, they answered the VEQ, SMS, UVI, SSQ, VHPS, and demographic questions.

3.6 Hypotheses

Based on the related literature on body awareness, VBO, and agency, we expected higher ratings on these variables for higher levels of individualization. Further, we expected a reduced feeling of change and potentially increased eeriness ratings due to the increased similarity between user and avatar:

- H1.1: Higher individualization leads to increased SMS body and in-VR body awareness ratings.
- H1.2: Higher individualization leads to increased interoceptive accuracy.
- H2.1: Higher individualization leads to increased BO.
- H2.2: Higher individualization leads to increased AG.
- H2.3: Higher individualization leads to reduced CH.
- H2.4: Higher individualization leads to a higher UVI eeriness.

Further, we tested the following hypotheses concerning the relationship between SoE, VR UX, and body awareness:

- H3.1: Individualization affects the relationship between SoE and body awareness.
- H3.2: Individualization affects the relationship between avatar-related VR UX and body awareness.

Finally, we tested accordingly, on an exploratory basis, how the individualization of avatars affected non-avatar-related VR UX and mindfulness and how these were associated with body awareness.

4 Results

4.1 Analysis

All analyses were performed in R, using the R packages *jmv* and *stats*. Result plots were created using *ggplot2*. All models were tested against an alpha of .05. However, for a more precise insight and to account for the small sample size, post hoc analyses were also calculated for p-values $< .1$.

We calculated MANOVAs to test whether there were group differences in trait body awareness (MAIA). As multivariate normal distribution was not given, we report Wilks’ Λ. To analyze the effects of avatar individualization (H.1 - H.2), we calculated ANCOVA and MANCOVA models for each variable, depending on the respective number of measures. To regard inter-individual differences in trait body awareness, we included the sub-dimensions of the MAIA questionnaire as covariates in these analyses. However, we retained to report only the results regarding our manipulation. For all significant MANCOVA models, we calculated post hoc ANCOVA models. For all significant ANCOVA models, we calculated post hoc t-tests. As effect sizes in the ANCOVA models, we calculated partial η^2. For post hoc t-tests, we calculated Cohen’s d. For the post hoc t-tests, we report Bonferroni-Holm corrected p-values, p_{corr}.

To test for relations between SoE, VR UX, and body awareness (H3), we reduced the number of variables tested to the validated measures, including the SMS Body as the dependent variable and VEQ, UVI, and OIPS as potential predictors. For each predictor, we calculated a linear regression model, additionally including avatar individualization, to test for potential differences in slope between conditions. Again, we calculated partial η^2 as the effect size.

4.2 Demographics

All descriptive results are shown in Table 1. The MANOVA regarding MAIA ratings revealed no significant difference between the groups, $F(16,148) = 0.966, p = .497$.

4.3 Effects of Avatar Individualization

4.3.1 Body Awareness and Mindfulness

In line with H1.1, the MANCOVA model on body awareness, including the post-VR variable SMS Body and the in-VR body awareness ratings, revealed a significant effect, $\Lambda = 0.741, F(12,146) = 1.96, p = .049$. The univariate post hoc ANCOVA models revealed a significant effect on Noticing External, $F(2,75) =$

Table 1: Descriptive results of body awareness, SoE, and VR UX.

	Range	Generic M (SD)	Customized M (SD)	Personalized M (SD)
State Body Awareness				
SMS Body	[1 – 5]	3.72 (0.58)	3.68 (0.65)	3.37 (0.63)
Noticing External	[1 – 10]	4.96 (2.56)	4.69 (2.89)	3.14 (2.09)
Noticing Internal	[1 – 10]	7.68 (1.49)	7.48 (1.79)	7.25 (1.48)
Body Listening	[1 – 10]	7.54 (1.50)	6.31 (2.42)	6.71 (1.70)
Attention Regulation	[1 – 10]	8.07 (1.61)	7.24 (1.57)	7.64 (1.45)
Visual Attention	[1 – 10]	2.96 (1.71)	2.93 (1.91)	3.43 (1.55)
HCT (post - pre)	[0 – 1]	0.00 (0.13)	-0.02 (0.12)	0.04 (0.11)
Mindfulness				
SMS Mind	[1 – 5]	3.48 (0.61)	3.31 (0.65)	3.40 (0.76)
Noticing Thoughts	[1 – 10]	6.46 (2.46)	6.55 (2.64)	5.96 (2.28)
Noticing Affect	[1 – 10]	4.61 (2.22)	3.59 (2.10)	4.36 (2.23)
Thought Watching	[1 – 10]	4.61 (2.04)	4.41 (2.64)	5.25 (2.63)
Sense of Embodiment (SoE)				
VEQ BO	[1 – 7]	4.08 (1.45)	3.86 (1.51)	4.92 (1.28)
VEQ Agency	[1 – 7]	5.91 (0.76)	5.29 (1.25)	5.92 (0.95)
VEQ Change	[1 – 7]	2.34 (1.25)	2.75 (1.58)	2.85 (1.73)
inVR BO	[1 – 10]	5.36 (2.13)	4.38 (2.29)	6.43 (1.60)
inVR Agency	[1 – 10]	6.32 (1.91)	6.03 (1.88)	7.29 (1.82)
inVR Change	[1 – 10]	3.21 (2.41)	3.66 (2.47)	3.93 (2.39)
Virtual Human Plausibility				
MVE	[1 – 7]	5.84 (0.93)	5.57 (1.20)	5.84 (1.05)
ABP	[1 – 7]	5.56 (0.85)	5.39 (0.85)	5.64 (0.92)
Avatar Uncanniness				
UVI Humanness	[1 – 7]	3.16 (1.10)	3.13 (1.17)	3.74 (1.32)
UVI Attractiveness	[1 – 7]	4.68 (0.78)	4.54 (0.84)	4.45 (0.89)
UVI Eeriness	[1 – 7]	3.06 (0.71)	2.84 (0.67)	3.91 (0.65)
inVR Satisfaction	[1 – 10]	6.93 (1.98)	6.69 (1.89)	7.04 (1.90)
inVR Discomfort	[1 – 10]	2.57 (1.57)	3.00 (2.02)	2.86 (2.05)
Sense of Presence OIPS	[1 – 10]	6.89 (1.55)	6.86 (1.73)	6.43 (1.89)
Simulation Sickness				
SSQ Nausea	[-220 – 220]	-0.99 (26.42)	-8.22 (22.48)	-2.38 (22.73)
SSQ Oculomotor	[-220 – 220]	-3.66 (16.16)	-11.24 (19.50)	0.81 (19.17)
SSQ Disorientation	[-220 – 220]	0.96 (17.82)	-8.16 (23.97)	13.92 (36.93)

$4.60, p = .013, \eta^2 = .109$, and Body Listening, $F(2,75) = 3.39, p = .039, \eta^2 = .083$, but not on SMS Body, $F(2,75) = 3.03, p = .054, \eta^2 = .075$, Noticing Internal, $F(2,75) = 0.73, p = .484, \eta^2 = .019$, Attention Regulation, $F(2,75) = 1.89, p = .158, \eta^2 = .048$, or Visual Attention, $F(2,75) = 0.58, p = .561, \eta^2 = .015$.

Post hoc comparisons for SMS Body revealed a significant difference between generic and personalized avatars, $t(75) = 2.58, p_{corr} = .035, d = .715$, and between customized and personalized avatars, $t(75) = 2.52, p_{corr} = .035, d = .696$, but not between generic and customized avatars, $t(75) = 0.07, p_{corr} = .943, d = .019$, see Fig. 4, a. Accordingly, post hoc comparisons for Noticing External revealed a significant difference between generic and personalized avatars, $t(75) = 2.40, p_{corr} = .038, d = .665$, and between customized and personalized avatars, $t(75) = 2.77, p_{corr} = .021, d = .764$, but not between generic and customized avatars, $t(75) = 0.37, p_{corr} = .714, d = .099$, see Fig. 4, b. Post hoc comparisons for Body Listening did not reveal a significant difference between conditions after p-corrections, see Fig. 4, c.

Contrary to H1.2, an ANCOVA on post-HCT, including pre-HCT as a control, did not reveal a significant result, $F(2,66) = 1.90, p = .062$. An exploratory MANCOVA model on mindfulness, including the SMS Mind and the in-VR mindfulness variables, did not reveal a significant effect, $\Lambda = 0.849, F(8,144) = 1.54, p = .150$.

4.3.2 Sense of Embodiment

The MANCOVA model on SoE, including the VEQ dimensions and the in-VR SoE ratings (H.2.1 - H.2.3), revealed a significant effect, $\Lambda = 0.736, F(12,140) = 1.93, p = .035$. The univariate post hoc tests revealed a significant effect on VEQ BO, $F(2,75) = 3.67, p = .030, \eta^2 = .089$, and inVR BO, $F(2,75) = 6.45, p = .003, \eta^2 = .147$. It revealed a significant effect on VEQ AG, $F(2,75) = 3.67, p = .030, \eta^2 = .089$, but not inVR AG, $F(2,75) = 3.06, p = .053, \eta^2 = .075$. We found no significant effect on VEQ CH, $F(2,75) = 0.43, p = .654, \eta^2 = .011$, nor inVR CH, $F(2,75) = 0.27, p = .763, \eta^2 = .007$.

Post hoc comparisons for VEQ BO revealed no significant difference between generic and personalized avatars, $t(75) = 1.48, p_{corr} = .288, d = .407$, nor between customized and personalized avatars, $t(75) = 2.42, p_{corr} = .054, d = .670$, or generic and customized avatars, $t(75) = 0.97, p_{corr} = .334, d = .262$, see Fig. 4, d. Post hoc comparisons for inVR BO revealed a significant difference between customized and personalized avatars, $t(75) = 3.49, p_{corr} = .002, d = .967$, but not between generic and personalized avatars, $t(75) = 1.47, p_{corr} = .146, d = .406$, or generic and customized avatars, $t(75) = 2.08, p_{corr} = .082, d = .561$. Post hoc comparisons for VEQ AG revealed no significant difference between generic and personalized avatars, $t(75) = 0.33 p_{corr} = .741, d = .092$, nor between customized and personalized avatars, $t(75) = 1.99, p_{corr} = .101, d = .549$, or generic and customized avatars, $t(75) = 2.37, p_{corr} = .061, d = .641$, see Fig. 4, e. Post hoc comparisons for inVR AG revealed no significant difference between generic and personalized avatars, $t(75) = 1.34, p_{corr} = .362, d = .373$, nor between customized and personalized avatars, $t(75) = 1.96, p_{corr} = .160, d = .543$, or generic and customized avatars, $t(75) = 0.63, p_{corr} = .529, d = .171$.

4.3.3 VR UX: Avatar-Related Measures

In line with H2.4, a MANCOVA model on the uncanny valley effect, including UVI, and the in-VR items Satisfaction and Discomfort, revealed a significant effect, $\Lambda = 0.592, F(10,142) = 4.25, p < .001$. The univariate post hoc tests revealed a significant effect on UVI Eeriness, $F(2,75) = 19.74, p > .001, \eta^2 = .345$, but no significant effect on UVI Humanness, $F(2,75) = 1.89, p = 0.159, \eta^2 = .048$, UVI Attractiveness, $F(2,75) = 0.33, p = 0.716, \eta^2 = .009$, Satisfaction, $F(2,75) = 0.39, p = 0.680, \eta^2 = .010$, or Discomfort, $F(2,75) = 0.59, p = 0.557, \eta^2 = .015$. Post hoc comparisons for UVI Eeriness revealed a significant difference between generic and personalized avatars, $t(75) = 4.12, p_{corr} < .001, d = 1.14$, and between customized and personalized avatars, $t(75) = 5.10, p_{corr} < .001, d = 1.411$, but not between generic and customized avatars, $t(75) = 1.01, p_{corr} = .315, d = .273$, see Fig. 4, f.

A MANCOVA on virtual human plausibility, including the post-VR variables VHPS ABP and VHPS MVE, did not reveal a significant effect, $\Lambda = 0.980, F(4,148) = 0.38, p = .826$.

4.3.4 VR UX: Non-Avatar-Related Measures

An exploratory ANCOVA model on SoP, including the OIPS, revealed no significant effect, $F(2,75) = 0.71, p = .493$.

An exploratory MANOVA model on simulator sickness, including the post-VR variables SSQ Nausea, SSQ Oculomotor, and SSQ Disorientation, did not reveal a significant effect, $\Lambda = 0.880, F(6,146) = 1.60, p = .150$.

4.4 Avatar Appearance, VR UX, and Body Awareness

The regression models, including SoE measures, revealed a significant impact of VEQ BO on SMS Body, $F(1,80) = 4.62, p = .035, \eta^2 = .055$, but, contrary to H3.1, not a significant interaction, $F(2,80) = 0.36, p = .699, \eta^2 = .009$. They revealed a significant positive relationship between VEQ AG and body aware-

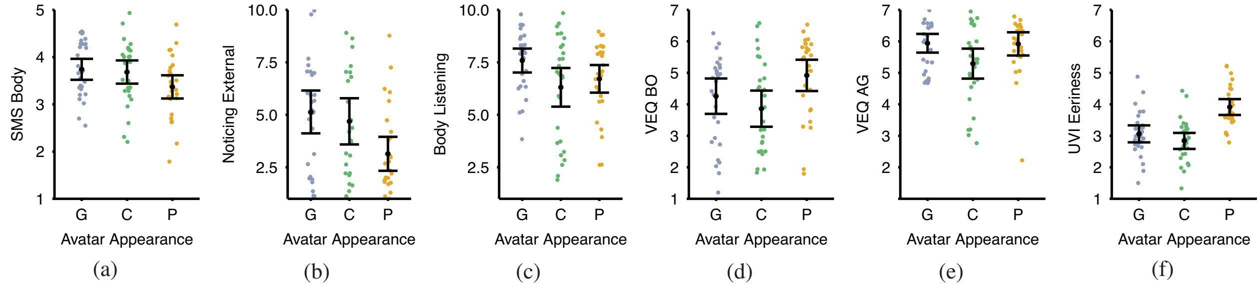

Figure 4: Effects of avatar individualization on body awareness and VR UX. The figure depicts the means, distributions, and standard errors. G = Generic, C = Customized, P = Personalized.

ness, $F(1,80) = 8.14, p = .006, \eta^2 = .092$, but no significant interaction, $F(2,80) = 0.74, p = .480, \eta^2 = .018$. Finally, they revealed neither a significant impact of VEQ CH on SMS Body, $F(1,80) = 0.05, p = .831, \eta^2 < .001$, nor a significant interaction, $F(2,80) = 1.22, p = .300, \eta^2 = .030$.

Contrary to our hypothesis H3.2, the regression model including UVI Eeriness revealed neither a significant impact of UVI Eeriness on SMS Body, $F(1,80) = 0.62, p = .433, \eta^2 = .008$, nor a significant interaction, $F(1,80) = 2.22, p = .116, \eta^2 = .053$. The regression model including UVI Humanness revealed neither a significant impact of UVI Humanness on SMS Body, $F(1,80) = 0.12, p_{corr}. = .727, \eta^2 = .002$, nor a significant interaction, $F(1,80) = 0.36, p = .697, \eta^2 = 009$. The regression model including UVI Attractiveness revealed neither a significant impact of UVI Attractiveness on SMS Body, $F(1,80) = 0.02, p = .889, \eta^2 < .001$, nor a significant interaction, $F(1,80) = 0.61, p = .545, \eta^2 = .015$.

A regression model including OIPS revealed a significant impact of OIPS on body awareness, $F(1,80) = 6.71, p = .011, \eta^2 = .077$, but no significant interaction, $F(2,80) = 0.31, p = .734, \eta^2 = .008$.

5 Discussion

Our findings demonstrate that the design of an avatar as a second perceivable body next to our physical body can impact body awareness in VR. Concerning our primary objectives, we came to the following conclusions: (1) Our results indicate that while the avatar customization hardly had any impact, the personalization negatively affected body awareness and partly affected avatar-related VR UX but not non-avatar-related VR UX. (2) Our study revealed a relationship between VR UX and body awareness, especially regarding the SoE and SoP. (3) The relationship between VR UX and body awareness did not differ between the levels of individualization. In the following, we discuss our results in depth.

5.1 Personalization Increases VBO and Eeriness

In our study, avatar individualization affected VR UX. Embodied personalized avatars led to significantly increased VBO (H2.1), persisting to some extent beyond the VR session. However, participants also experienced their personalized avatars as eerier than generic or customized ones (H2.4). These findings align with existing literature where similar personalization led to heightened VBO [35, 44, 61, 76]. The link between personalization and eeriness aligns with the uncanny valley concept. However, it is worth noting that Salagean et al. [61] did not find this effect when comparing personalized to less personalized avatars. The feeling of agency (H2.2) appeared to differentiate between generic and customized avatars, but not significantly. This finding, too, aligns with previous literature indicating that manipulations of appearance have a stronger influence on VBO than on agency [52, 61, 78]. In addition, the overall lack of difference between generic and customized avatars could be explained by a deeper analysis of avatar preferences, as investigated by Fribourg et al. [26]. They found that a custom avatar chosen by participants to match their appearance was not necessarily preferred in terms of SoE and depended on the in-VR task. Another interesting observation is the absence of an effect on the VEQ Change (H2.3) [60]. This result suggests that the avatars' appearance, at least in our specific setting, does not alter the perception of one's physical body. However, VEQ Change was designed to evaluate applications in which the avatar is dissimilar to the user's appearance, creating a behavioral or experiential response. In this study, we aimed for a high similarity between the avatar and the user. Accordingly, our avatars might not have evoked a Change experience.

5.2 Body Awareness and VBO

The degree of avatar individualization significantly impacted self-reported body awareness ratings (H1.1) but not interoceptive accuracy (H1.2). Participants reported a significantly lower level of body awareness while embodying their personalized avatars, both during and after the VR experience, compared to embodying a generic or customized avatar. One explanation for this adverse effect of personalized avatars is a possibly increased cognitive load. A study by Mejia-Puig et al. [49] demonstrated that avatars inducing higher VBO also elevated cognitive load. Considering body awareness in the context of embodied cognition, increased cognitive load in VR could reduce the cognitive capacity available for processing internal bodily states. Since we did not measure cognitive load, it remains for future work to determine to what extent cognitive load contributes here and how it can be minimized. Regardless, our findings on the relationship between VBO, agency, SoP, and body awareness challenge this explanation. They indicate a positive relationship unaffected by the degree of individualization (H3.1, H3.2). These results align with related studies [15, 17, 20], contradicting the notion that increased VBO necessarily reduces body awareness. There seems to be an additional need for an explanation as to why personalized avatars reduce body awareness.

5.3 The Role of VR UX

Adhering to Wienrich et al.'s [79] guidelines, accounting for VR UX measures could bring further insights into the effect of avatar personalization on body awareness. In our study, next to an increased cognitive load, increased eeriness ratings could explain the effect of personalization on body awareness. Participants found their personalized avatars eerier than the other conditions, potentially triggering an uncanny valley response despite high VBO. This could have resulted in signals from the physical body being suppressed. However, we found no relationship between UVI and body awareness (H3.2), arguing against this explanation. Across conditions, eeriness did not negatively affect body awareness. Still, investigating in more detail whether controlling for eeriness mediates an effect of personalization on body awareness would be insightful.

A final explanation for the effect of personalization on body awareness could be a distraction by observing the details of the personalized avatar. For most participants, it was the first time embodying a personalized avatar. We aimed to minimize distraction by concealing the virtual mirror during body awareness exercises [17, 58], and participants did not report a preference for visuals over other signals. However, some participants still commented on the details of their personalized avatars. Further research is needed to gauge whether familiarity with a personalized avatar over multiple VR experiences mitigates their adverse effects on body awareness.

5.4 How Can We Find Balance?

The question arises to what extent the use of personalized avatars remains an option for therapeutic applications or to what extent a negative effect on body awareness can or needs to be avoided. In therapeutic settings, maximum personalization of avatars is not always possible, if only for financial reasons. But are personalized avatars a desirable goal if they reduce body awareness?

Defining the trade-off between avatar appearance and the possible consequences for body awareness and other critical psychological factors in therapy is crucial. Is a personalized avatar more likely to be perceived as a part of one's body, blurring the boundaries between the physical and the real body? Mind-body interventions often aim to direct attention to internal bodily signals [48]. Avoiding personalized avatars might be prudent given our body awareness and eeriness results. At least, determining which factors are decisive in avoiding undesirable reductions in body awareness induced by the avatar's appearance is essential. However, other therapeutic areas may build on a temporal reduction of body awareness. For example, an excessive fixation on the body as a symptom of a body image disorder could benefit from a temporal reduction of body awareness [21, 53]. In this context, it would be valuable to explore how a relationship between avatar appearance, VBO, and body awareness contributes to the success of such an application.

The VBO serves as a foundation for various VR phenomena that could be useful in VR mind-body interventions, such as the Proteus effect [45]. In our study, VBO positively predicted body awareness. Therefore, regardless of the type of avatar used, we deem it essential to strive for a strong sense of VBO within the appropriate range. To further explore the relationship between personalized avatars, VBO, body awareness, and the experience of eeriness, future studies could take inspiration from research investigating the effects of subtle differences in avatar appearance [61]. Understanding the dynamics between these constructs will contribute to developing more sophisticated guidance in avatar selection for therapeutic scenarios.

5.5 Limitations

Our results provide essential insights into the interaction of body and avatar perception. Regardless, our findings are limited. While we used avatars with similar realism, detailing, and anthropomorphism, our personalized avatars differed slightly from the other conditions. It has been indicated that the effects of personalization also arise when controlling for avatar creation and when using the same avatar type for personalized or generic avatars [76]. However, a study examining subtle differences in personalization and rendering realism could provide valuable insights into this matter [61].

In addition, it is crucial to discuss our choice of generic avatars. We chose avatars that could be interpreted as white, relatively thin, and young adults. In the customized condition, participants mainly chose avatars that resembled our generic avatars, only differing in hair color or muscle mass. We take this as an indicator that the generic avatars were well-suited for our particular sample. However, using these avatars in a more diverse sample could lead to considerable variance in the similarity between participants and avatars. Since our sample is limited, generalizability needs further investigation. Using generic avatars is always likely to result in a variance in similarity. Thus we recommend controlling for similarity, for example, by assessing perceived self-similarity or self-attribution as parts of self-identification [29], as proposed by Fiedler et al. [23].

Further, we are aware that the SMS Body, as part of a mindfulness questionnaire, and our in-VR items do not fully cover the construct of body awareness. So far, few measures refer to a subjective state of body awareness. There is a lack of valid measures to do justice to the dimensionality of body awareness while still referring to the current state of the participant rather than their trait body awareness. Gathering the participants' subjective responses to the VR experience could have given further insights into our data collection. Especially an inclusion of qualitative measures, such as post-experience interviews or the newly-introduced tool InwardVR by Haley et al. [31], could help gain more nuanced knowledge in future work.

Regarding the objective measures used in this study, the absence of an HCT effect can be attributed to several factors. It is worth discussing whether interoceptive accuracy, assessed via HCT, is valuable in the context of short-term effects. While it has been under debate as a tool in assessing body awareness [11], the HCT is often considered a moderately stable measure of interoceptive accuracy [72] with a relatively high inter-individual variance. Thus, to reveal potential short-term effects [24], testing with larger sample sizes and reducing variance by forming subsets seems necessary.

Finally, we have to discuss the therapeutic potential of our experiment. Body awareness is integral to mind-body interventions, and our body awareness movement tasks resemble standard therapeutic methods. However, we conducted our experiment with a non-clinical sample and did not use therapeutic framing. Our findings on the relationship between body awareness and VR UX are a necessary step in VR-oriented mind-body interventions. However, the study provides rather fundamental insights that can serve as a basis for a more clinical setting in future work.

6 Conclusion

Body awareness is a crucial determinant of the success of mind-body therapy approaches. Our study investigated the impact of avatar individualization and VR UX on body awareness in VR. In our work, customization of avatars had minimal influence, whereas personalization led to reduced body awareness, increased virtual body ownership (VBO), and an increased uncanny valley effect. Other VR UX measures, such as virtual human plausibility and simulation sickness, were not affected. Further, irrespective of the condition, our results revealed a significant relationship between the VBO and sense of presence (SoP) and body awareness.

These results demonstrate the importance of examining both VR UX measures and the relationship between VR UX and body awareness in a therapeutic context. In our study, personalization, while causing a high VBO, reduced body awareness even though we found a generally positive relationship between the two variables. This result highlights that the relationship between VR UX and body awareness is not always straightforward. Even designs that seem obvious at first glance might lead to undesirable outcomes that would be overlooked if not controlled for. Future research should clarify the complex interplay between personalization, VBO, eeriness, and body awareness. Understanding these interrelationships can inform the design and development of VR interventions, especially in therapeutic contexts, where the manipulation of avatar appearance and VR UX might influence targeted outcomes.

Acknowledgments

This research has been funded by the German Federal Ministry of Education and Research in the project ViTraS (16SV8219 and 16SV822) and VIA-VR (16SV8444 and 16SV8445). We thank Niklas Döllinger for his support with our illustrations. Erik Wolf gratefully acknowledges a Meta Research PhD Fellowship.

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6 Virtual Body Swapping: A VR-Based Approach to Embodied Third-Person Self-Processing in Mind-Body Therapy

Döllinger, N., Mal, D., Keppler, S., Wolf, E., Botsch, M., Israel, J. H., Latoschik, M. E., & Wienrich, C. (2024). Virtual body swapping: A VR-based approach to embodied third-person self-processing in mind-body therapy. *Proceedings of the CHI Conference on Human Factors in Computing Systems*. doi: 10.1145/3613904.3642328

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This chapter was published in the CHI '24: Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems.

Author Contributions

Nina Döllinger conceptualized the experimental design, supervised the development of the body swap system, supervised the data collection, performed the analysis, and took the lead in writing the manuscript. David Mal developed parts of the Unity application, including the multi-user application, the body swap system, the experimental environment, and the avatar animation system. Sebastian Keppler developed parts of the Unity application, including the multi-user application and the body swap system. Erik Wolf developed parts of the Unity application, including the experimental environment and the avatar animation system. Johann Habakuk Israel conceived parts of the original project idea and supervised the development. Mario Botsch provided the avatar reconstruction framework. Carolin Wienrich and Marc Erich Latoschik conceived parts of the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

Virtual Body Swapping: A VR-Based Approach to Embodied Third-Person Self-Processing in Mind-Body Therapy

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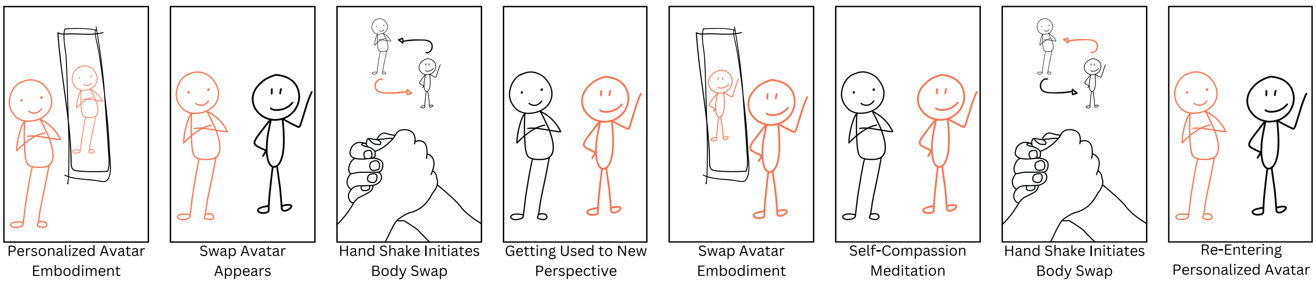

Figure 1: This figure shows the virtual body-swapping process used in our study. The orange color indicates which avatar is currently controlled by the participants.

ABSTRACT

Virtual reality (VR) offers various opportunities for innovative therapeutic approaches, especially regarding self-related mind-body interventions. We introduce a VR body swap system enabling multiple users to swap their perspectives and appearances and evaluate its effects on virtual sense of embodiment (SoE) and perception- and cognition-based self-related processes. In a self-compassion-framed scenario, twenty participants embodied their personalized, photorealistic avatar, swapped bodies with an unfamiliar peer, and reported their SoE, interoceptive awareness (perception), and self-compassion (cognition). Participants' experiences differed between bottom-up and top-down processes. Regarding SoE, their agency and self-location shifted to the swap avatar, while their top-down self-identification remained with their personalized avatar. Further, the experience positively affected interoceptive awareness but not self-compassion. Our outcomes offer novel insights into the SoE in a multiple-embodiment scenario and highlight the need to differentiate between the different processes in intervention design. They raise concerns and requirements for future research on avatar-based mind-body interventions.

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CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05
https://doi.org/10.1145/3613904.3642328

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Laboratory experiments*; *Empirical studies in HCI*.

KEYWORDS

Virtual reality, embodiment, self-compassion, body awareness, body swap, perspective taking.

ACM Reference Format:
Nina Döllinger, David Mal, Sebastian Keppler, Erik Wolf, Mario Botsch, Johann Habakuk Israel, Marc Erich Latoschik, and Carolin Wienrich. 2024. Virtual Body Swapping: A VR-Based Approach to Embodied Third-Person Self-Processing in Mind-Body Therapy. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA*. ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3613904.3642328

1 INTRODUCTION

Virtual reality (VR) and avatars find increasing use in psychotherapeutic practices. VR systems offer diverse opportunities, encompassing presence in a virtual environment and facilitating diverse perspectives and the potential for embodying differently appearing virtual bodies. The exposure to such virtual bodies, avatars, can elicit a sense of embodiment (SoE) toward them, a feeling of incarnating it in the virtual environment [42]. Current studies on avatar-based SoE mainly involve users embodying a single avatar with a specific appearance. These studies investigate how the embodiment of and control over different-looking avatars affects the users' SoE [81], their relationship to their physical body [22, 53, 83], or other therapy-related outcomes [15, 27]. What unifies most of these studies is that they confront the user with a single avatar that either looks like themselves, is slightly altered, or differs significantly from the user's appearance. What has been explored less so far is what happens when users embody multiple avatars, either successively [27] or simultaneously [36], and how such a body swap affects self-perception in mind-body interventions.

Perspective shifts are frequently used in therapeutic scenarios [9, 35]. Patients create distance to themselves [43] by imaginary taking on a different perspective or taking different perspectives on a scene by role-playing with others. We present a VR system that allows body swapping in real-time. Users exchange their avatars and perspectives with other users by a handshake. The exchange partners can be in the same physical space or interact with each other remotely. In an evaluation study with personalized photorealistic avatars and a self-compassion meditation task, we investigate the following: (1) Does body swapping per se, and (2) does the visibility of the swap avatar affect the SoE towards one's personalized avatar and the swap avatar, interoceptive awareness, and self-compassion. We further qualitatively elaborated on the user experience during the body-swapping process.

Our contribution is twofold. We present a distributed body swap system allowing for real-time perspective switches. Additionally, we contribute new insights into the SoE toward personalized and generic avatars during a self-compassion-oriented body swap scenario and put them in the context of body perception. Virtual body swap experiences can be an innovative milestone for all interventions that work with perspective change. Therefore, we contribute groundbreaking results for such systems' effects and future design.

2 RELATED WORK

Increasing numbers of mental disorders, including those arising during and after the COVID-19 pandemic [16, 46], reinforce the demand for a range of intervention options beyond substance-oriented therapy. So-called mind-body interventions, in particular, are increasingly the focus of attention in treating mental disorders [73]. Mind-body interventions, also referred to as mind-body therapy, mindfulness-based therapy, or meditation-based interventions, are a broad field of therapy forms under the guise of connecting mind and body, creating conscious self-awareness, and increasing mindfulness [34, 77].

While mind-body interventions have not always been part of conventional medicine, in recent decades, more and more evidence of their efficacy in the treatment of mental disorders has emerged, making them an increasing part of the therapeutic landscape alongside traditional psychotherapy and drug-oriented medicine [77]. While some are rooted in ancient practices, most modern mind-body interventions are based on the philosophical approach of the theory of embodied cognition. Similar to approaches like somaesthetics by Shusterman [65] and somaesthetic design, which combines embodied cognition with aesthetics, they take a holistic approach to the design and structure of therapeutic exercises. They treat the body, the soma, both as a means of expression and as the basis of all perceptions and thoughts. Grounded in the relationship between mind, body, and behavior, these interventions aim to strengthen the positive effects between those [77]. While the specific methods are diverse, mind-body interventions usually include a combination of conscious physical movement exercises, mindfulness or meditation practices, and body-based attention exercises, including breathing techniques.

2.1 Mind- and Body-Oriented Self-Related Processes

How mind-body interventions affect therapeutical outcomes can be explained by self-related processes [12]. These processes can be roughly classified into three categories: pre-reflective embodied, cognitive-conceptual, and processes supporting self-regulation by combining perceptive and cognitive processing characteristics. Britton et al. [12] assign the self-related processes to a continuum between a more embodied "self as subject" and a more conceptual "self as object". The more body-oriented processes, including interoception, sense of agency, sense of body ownership, sense of boundaries, and perspectival self (or self-location), occur here under the umbrella of embodiment and align with the self as subject. The more cognitive or mind-related processes, including narrative self, self-criticism, self-compassion, self-evaluation, self-esteem, and rumination, occur under the conceptual self or self as object.

It is important to emphasize that framing embodiment as predominantly perceptual is not necessarily exhaustive. Embodiment, too, has been described as a dual experience of perceiving and being perceived, both as something that we are (being a body, the body as subject, similar to the self as subject) and that we own (having a body, the body as object, similar to the self as object) [41]. This understanding of embodiment aligns more with an alternative, body-centric description of the overall self-related processes. However, in this work, we adopt the definition of Britton et al. [12] to delineate different internal processes.

Mind-body interventions can positively modify a range of self-related processes and, in turn, affect their interrelation. How these self-related processes mediate between the respective intervention method and its therapeutic goal has yet to be thoroughly investigated. For some cognition-related processes, relationships have already been identified. Notably, reducing rumination is associated with improved outcomes for mental health. Other processes, such as self-compassion, have been indicated to have a positive relationship with well-being [12]. Concerning the more body-related processes, the available data is thinner.

However, while they do not necessarily explain the mediative role of embodied self-related processes, some studies highlight the effects of mind-body interventions on them. For example, Dambrun et al. [18] found an effect of mindfulness meditation practice on the sense of self-location. Hanley et al. [39] found a decreasing effect of meditation exercises on perceived body boundaries.

2.2 Taking Perspectives on the Self

One method to investigate the possible effects of embodied self-related processing on further outcomes is to transfer the experience to VR. VR allows us to experience the body in a new way by changes in appearance, body shape, and movement of an embodied avatar, changes in the perspective on the supposedly "own" avatar, and so on. Hence, various possibilities exist to impact body-related, perceptual self-related processes in VR.

Beyond VR-based meditation applications without visual body representations [24], the embodiment of virtual bodies, so-called avatars, as a possibility for self-reflection has been repeatedly proposed in recent years [17, 25, 58]. This includes exploring perspective changes or out-of-body simulations in VR, transitioning from a first-person perspective (1pp) of oneself to a third-person perspective (3pp) or another virtual character. For instance, Osimo et al. [58] and Slater et al. [66] investigated virtual self-counseling. Subjects switched perspectives between their virtual selves, an avatar designed to resemble them, and a virtual representation of Sigmund Freud. This body swap increased the perceived support of the conversation compared to swapping between two self-avatars or even a pre-scripted conversation with Sigmund Freud. The authors explain this effect by the distance gained by switching to the Freud avatar. However, they did not investigate whether a perceptual distance to self-perception had actually arisen, for example, through a change in self-location or interoception.

Falconer et al. [27] provide another example of virtual perspective in self-related processing. In a self-compassion exercise with depression patients, they investigated the effect of transitioning from an adult to a child avatar. Subjects reported increased self-compassion, reduced self-criticism, and reduced depression symptoms. However, no comparison was made to a condition without body swapping or between different embodiment conditions. In an augmented reality self-compassion exercise, Cebolla et al. [15] showed that shifting perspective to another person, gaining an outside view of one's body during a self-compassion meditation, affected subjects' interoception, self-compassion, and overall mindfulness, comparable to the results of a meditative imagination exercise. Finally, Landau [44] presented a method for virtual self-encounter and embodiment of another person via 360° videos. Based on a conference demonstration, they reported some positive effects, meaningful moments, and altered body perception.

As an interim conclusion, these first studies show the potential of body swapping for therapeutical aims. Past research has shown that the embodiment of an avatar can affect the user's experience and behavior. To fully understand how body swapping and the sequential embodiment of multiple avatars in VR contribute to the future of mind-body interventions, it is crucial to investigate the effects on therapy-relevant variables. However, measuring these target variables covers only part of the possible effects of a body swap scenario. Examining moderating variables is necessary to pinpoint what mechanisms might lie behind them. Following approaches to systematically investigate the relationship between specific VR-related behavior mechanisms and therapy-relevant measures [82], our work aims at two sets of variables. We investigate the effects of a body-swap scenario on self-related processes mediating mind-body interventions, both on a perceptual (e.g., interoception) and a cognitive layer (e.g., self-compassion). Additionally, we target gaining new insights into how users perceive the two sequentially embodied avatars, highlighting effects on the SoE. Finally, we combine these two sets of variables and examine how they are related.

2.3 Embodied Self-Related Processes in Virtual Body Swapping

2.3.1 Sense of Virtual Embodiment. The SoE can be deduced from embodied self-related processes and transfers them to the processing of avatars. SoE, too, differentiates between body ownership (sense of virtual body ownership, VBO), agency (sense of agency over the avatar), and perspectival self (sense of self-location in the avatar) [42]. Moreover, the SoE is often extended by further perceptual components, including self-attribution (the extent to which one finds oneself reflected in the avatar), change (the extent to which one feels that the avatar has an impact on the self), or self-similarity (the extent of similarity perceived between oneself and the avatar).

Various studies have investigated which factors enhance or reduce SoE [52, 81]. For example, the VBO is affected by the similarity between avatar and user, the degree of realism, and especially by personalization [62, 81]. Conversely, the sense of agency is influenced by the accuracy with which the avatar follows the user's movements or by the time spent in VR [52]. Regarding the perspective on the avatar, a 1pp seems to be more critical than a 3pp [20]. Prolonged mirror exposure does not consistently increase SoE [52]. Yet, confronting users with their mirror image during body movements is a common method to accustom them to their virtual appearance [68]. Considering a body swap's potential to stimulate higher-level self-related processes, it is reasonable to consider such events' influence on the perceptual level of self- and avatar-processing.

In the body-swapping studies cited above, the focus concerning the SoE was predominantly on the acutely controlled avatar. Studies examined whether participants experience a SoE toward a virtual Freud [58, 66], a virtual "inner child" [27], or the experimenter [15]. However, the avatar, which participants embody first, is introduced by appearance or framing as the current "self-avatar". It is, thus, thematically closer to the participants. Hence, it is crucial to consider how the relationship to this self-avatar changes through the body swap and how it potentially affects other self-related processes.

The impact of embodiment or exposure to two avatars simultaneously or in short successive intervals is part of the current research on SoE. For example, Guterstam et al. [36] reported a "dual full-body ownership illusion" and a "dual self-location" with proximate avatars presented from 1pp. Similarly, Verhulst et al. [78] observed parallel motor adaptation to two avatars controlled in short alternation, differing slightly in movements from the participants and each other. Other studies have used perspective changes on a single avatar [17, 31]. However, subjects in these studies retained control over the movements of the different avatars at all times, possibly limiting the association of external perspective change with distancing from the self-avatar. Additionally, most of these studies did not focus on self-related processes in a mind-body-oriented scenario. Building on the existing research, we pose four research questions regarding the SoE:

RQ 1.1: Does a virtual body swap affect SoE toward a personalized self-avatar?
RQ 1.2: Does the visibility of a swap avatar affect the SoE toward the personalized avatar?
RQ 1.3: Do participants experience SoE toward a non-personalized swap avatar while their personalized avatar is visible in the same virtual space?
RQ 1.4: In body swapping, how does the SoE toward a personalized avatar relate to self-related processes?

2.3.2 Interoception. Besides the self-related processes within SoE, interoception is already part of different investigations in avatar embodiment. Interoception involves processing and integrating signals from within the body. Originally centered on awareness of bodily needs, the subjective interpretation of bodily signals has come into focus over the last few years. According to a definition by Garfinkel et al. [32], different facets of interoception can be distinguished. On the one hand, interoceptive accuracy describes the accuracy with which physical signals can be detected. Interoceptive awareness is the subjective perception of being in contact with the body signals. Interoceptive sensibility is the subjective confidence regarding interoceptive accuracy. Regarding its therapeutic relevance, interoception is the most studied construct among the perceptual-oriented self-related processes [12]. Low interoception is frequently associated with symptoms for body image disorders [11, 13], but has also been shown to affect pain management [8, 19] or self-harm [86]. Among others, interoception is mentioned as a driver of mind-body interventions [59] or as a mediator for higher-cognitive self-related processes, including self-compassion [4].

A reciprocal relationship between interoception and embodiment processing with artificial or virtual bodies has been established several times. Individuals with high interoceptive accuracy are less willing to engage with an unfamiliar body and report lower VBO [29, 51, 63]. Conversely, compared to a real-world exercise, Döllinger et al. [22] reported that realistic avatar embodiment could negatively affect interoceptive awareness. However, within a virtual experience, an increased VBO towards an avatar has been associated with increased interoceptive accuracy [29] or increased interoceptive awareness [15, 23, 25]. Regardless of the measure, interoception during avatar or artificial body part embodiment is significantly affected by how an SoE is targeted. This is evident in studies of visuo-tactile congruence [29], in which interoception benefited from congruence. It also becomes apparent in studies of avatar appearance, in which anthropomorphism has been found to support interoception [50] .

So far, studies on the effects of the perspective of a personalized avatar on SoE and interoception have only added a virtual mirror [22] with little to no effect on interoception, besides a minor shift in focus toward the mirror image. However, simultaneously processing two avatars in a body-swapping scenario could distract from one's body. So far, it has yet to be investigated how the embodiment of two different avatars in a short sequence impacts interoception. Hence, in this work, we pose the following research questions:

RQ 2.1: Does a virtual body swap affect interoception?
RQ 2.2: Does the visibility of a swap avatar affect interoception?

2.4 Virtual Reality and Conceptual Self-Related Processes: Self-Compassion

One concept that appeals in the field of mind-body-oriented virtual perspective-taking is self-compassion. Self-compassion is defined as "openness to and compassion for one's suffering, feelings of caring and kindness toward oneself, an understanding, nonjudgmental attitude toward one's shortcomings and failures, and recognition that one's own experience is part of the general human experience" [54]. Mind-body interventions positively impact self-compassion [12]. While a positive effect of self-compassion in the clinical context has been inconsistently evidenced [12], self-compassion and self-compassion exercises are part of various current mind-body interventions [33, 45, 71].

Changing perspective into a caretaker or experimenter's point of view can increase self-compassion [15, 27]. Exploring the effects of a body swap starting from a personalized avatar can expand on these results. Additionally, whether swapping into a different avatar is beneficial or whether a simple outside perspective provides more support for self-compassion has yet to be investigated. In our work, we, therefore, address the following questions on self-compassion:

RQ 3.1: Does a virtual body swap affect self-compassion?
RQ 3.2: Does the visibility of a swap avatar affect self-compassion?

2.5 Contribution

We present a distributed multi-user system allowing real-time body swapping and using photorealistic personalized avatars to maximize user-avatar similarity. Our study focuses on the evaluation of this system. Twenty participants performed a virtual body swap, followed by a self-compassion meditation. The swap partner was an unfamiliar assistant experimenter. The swap avatar was either an invisible entity (de-embody) to reduce the processing expense of being confronted with two avatars or a gender-matched, unfamiliar peer (re-embody). The research question-guided evaluation aimed to determine the pre-post effects of body swapping (swap effect) and of swap avatar visibility (condition: de-embody vs. re-embody) on SoE towards the personalized and the swap avatar (RQ 1.1-1.3). We explored the relationship between SoE toward the personalized avatar and the two involved self-related processes, interoceptive awareness and self-compassion (RQ 1.4). We investigated the effects of the swap and condition on interoceptive awareness (RQ 2.1-2.2) and self-compassion (RQ 3.1-3.2). Finally, we used semi-structured qualitative interviews to investigate the user experience of the body swap, avatars, and VR exercises.

3 SYSTEM DESCRIPTION

3.1 Avatars

The avatars were generated following the methods outlined in the work by Bartl et al. [7] and a photorealistic avatar reconstruction pipeline similar to that introduced by Achenbach et al. [1]. We employed a custom multi-DSLR camera setup to capture photos of each

Figure 2: The female (left) and male (right) swap avatars used during the experiment.

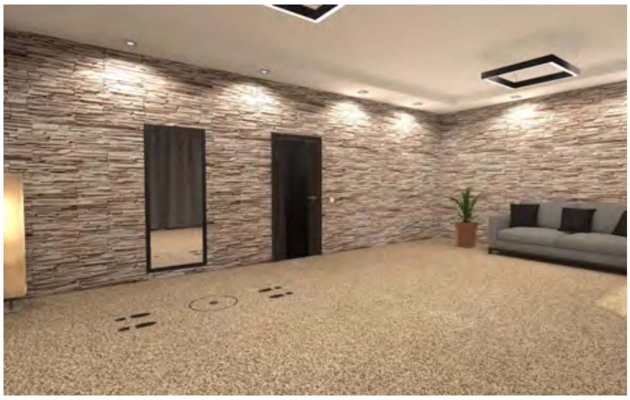

Figure 3: The virtual environment.

angle of the participant simultaneously. These photos served as the basis for creating a dense point cloud representation of the participant's body using Agisoft Metashape [2]. Subsequently, we applied a fully rigged template mesh from Autodesk Character Generator [3] to fit onto the point cloud. on which we applied a fully rigged template mesh. Finally, a personalized photorealistic texture was generated, including the addition of generic hand textures to match the participant's characteristics. For the body swap, we created one female and one male avatar representing the swap partner using the same procedure. To ensure unfamiliarity between the participants and these swap avatars, we scanned two external volunteers who were neither involved in the design nor the execution of the study. The two avatars are shown in Figure 2.

3.2 Virtual Environment

The virtual environment consisted in a virtual room spanning $4\,m \times 6\,m$ that was adapted from a Unity asset[1]. It is depicted in Figure 3. For certain tasks, a $1\,m \times 2\,m$ mirror was placed on the wall, accompanied by a whiteboard positioned to the right or left of the mirror, matching the participant's location. A circular marker on the floor indicated the participant's starting point at a distance of 1.5 m of the virtual mirror. As the experiment progressed, footprints on the left and right of the circular markers indicated the designated position for the body-swap interaction at a distance of 1.5 m to each other.

3.3 Hardware and Software

The VR system consisted of two Valve Index Head-Mounted Displays (HMD) [75] and two sets of Valve Index controllers (Knuckles; see Figure 4). Three SteamVR Base Stations 2.0 tracked all devices. The cable-bound HMDs provided a resolution of $1440\,px \times 1600\,px$ per eye, a refresh rate of 144 Hz, and a total field of view of $109.4^{\circ} \times 114.1^{\circ}$[2]. The VR setup included two high-end gaming PCs (NVIDIA GeForce RTX 2080 Ti, 32 GB RAM, Intel Core i7-9700K CPU, and Windows 10), running the participant's and the swap partner's VR environment. The VR experience was implemented using Unity (version 2020.3.25f1 LTS) [74] and integrated the VR system using SteamVR [76] and its corresponding Unity plug-in (version 2.6.1)[3].

Our application facilitates the embodiment of two avatars by two users within a shared virtual environment. We employed a client-server architecture for networking functionality, utilizing Photon Unity Networking[4] (version 2.40). A remote server instance operated at the University of Applied Science (HTW) Berlin, enabling seamless data transmission over a high-speed internet connection. At the University of Würzburg, two distinct workstations ran individual client application instances, each integrating one HMD. Each user's pre-processed avatar pose was promptly displayed within the local application instance and continuously streamed to the remote user's application instance with a refresh rate of 30 Hz. Modifications to application settings were shared between both instances, ensuring a synchronized shared virtual environment.

For body tracking, we used Captury's markerless tracking system [14, 69], employing eight FLIR Blackfly S BFS-PGE-16S2C RGB cameras attached to the laboratory ceiling to track participant's movements at a rate of 100 Hz. The cameras were connected to a powerful workstation (NVIDIA GeForce RTX 3080 Ti, 32 GB RAM, AMD Ryzen 9 5900x, Ubuntu 20.04.6 LTS) running Captury Live (version 248). The participant's fingers were tracked via the proximity sensors of the Knuckles. The body poses of the participant and the swap partner were continuously streamed to the VR system using a 1 GBit/s ethernet connection and integrated using Captury's Unity plug-in[5] [84]. Afterward, we retargeted the received body pose to the corresponding avatar. We merged it with the remaining tracking data from the VR system using Unity's avatar animation system and a custom-written retargeting script. We matched the avatars' hand movements to those captured by the Knuckles for increased stability and accuracy in the hand poses. Accordingly, a participant's hand movements were delivered to their HMD with

[1] https://assetstore.unity.com/packages/3d/props/interior/manager-office-interior-107709
[2] https://github.com/PeterTh/ovr_rawprojection
[3] https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647
[4] https://www.photonengine.com/pun
[5] https://captury.com/resources/

Figure 4: Handshake initiating body swap: Participant and their swap partner (left), participant avatar, and swap avatar in VR (right).

a motion-to-photon latency of 27 ms, aligning with the results of Warburton et al. [80]. The other body movements, captured by the markerless tracking, had a latency of 116 ms. Due to the server transmission, the movements of the swap partner were transmitted to the participant HMD with a latency increase of 66 ms. For comparison, the hand movements of the exchange partner were transmitted to the participant HMD with a latency of 93 ms.

3.4 Body Swap

The body swap included four steps: initiation, avatar swap, recalibration, and finalization. A handshake triggered the initiation as a shared consent gesture (Figure 4). Unity collider components attached to the avatars' hands facilitated collision detection to identify when the avatars' hands made contact. Upon handshake detection, a virtual loading bar appeared above the locked hands of the two users. The loading bar persisted for a three-second interval, visualizing the process state and allowing the users to prepare for the body swap. Releasing the handshake aborted the body swap and disabled the process bar. For the avatar swap, upon completing the handshake, a remote procedure call facilitated the body swap while both HMDs temporarily turned black. Each application instance changed the local user's self-avatar to correspond to the remote user's initial avatar. Both avatars were available on both local systems and were matched by unique avatar identifiers.

In the re-calibration phase, the local users' position and orientation within the virtual environment were adjusted to match the remote user's view. Therefore, each user's local tracking origin was rotated and translated, creating the illusion that they had swapped positions in the virtual environment, even though their physical bodies had not moved. Afterward, the primary experimenter re-calibrated the avatar retargeting on both local systems. For finalization, the HMDs were turned back on. The users now experienced the virtual environment from the other user's initial perspective while controlling the other user's avatar. Figure 5 depicts a participant's point of view during the body swap. The users could undo the body swap by initiating a second body swap, which followed the same procedure.

4 EVALUATION

4.1 Study Design

The study was carried out in a 2×2 mixed design. All participants started by embodying their personalized avatar before the body swap. Within each session, we assessed the SoE toward this avatar and the other dependent variables once before and once after the body swap (factor 1: pre-post swap effect). We varied between participants (factor 2: condition) whether they swapped into a visible swap avatar (re-embody) or whether they did not enter into a visible avatar in that process (de-embody). As dependent variables, we assessed the SoE towards their personalized avatars, interoceptive awareness, and self-compassion before and after the experience. We further assessed their SoE towards the swap avatar once after the body swap.

4.2 Participants

The study was conducted according to the Declaration of Helsinki and was approved by the ethics review board of the Institute Human-Computer-Media (MCM), University of Würzburg,[6]. Participants were recruited via the university's recruitment portal and received course credits in return. We excluded individuals in advance when (1) they had increased photosensitivity, (2) they felt uncomfortable with the idea of another person embodying their personalized avatar, (3) they had visual impairments that could not be corrected during the experiment, and (4) they were in any way familiar with the human model of their swap avatar. Overall, $N = 22$ individuals participated in our study, of which we had to exclude two due to technical problems. In the re-embody condition ($n = 10$), the age ranged between 20 and 32 years, $M = 22.90$ ($SD = 3.14$), with seven female and three male participants. In the de-embody condition ($n = 10$), the age ranged between 18 and 30 years, $M = 23.00$ ($SD = 3.58$), with six female and four male participants.

4.3 Measures

4.3.1 Avatar Perception. We assessed the SoE toward the self-avatar post-VR. Here, we used the Virtual Embodiment Questionnaire, VEQ [61], which provides 12 scales on three dimensions: VBO, agency, and change. The scales are presented on a 7-point Likert scale from 1 to 7. We added the scales proposed by Fiedler et al. [28], VEQ+, which pose 12 scales on three dimensions: self-location, self-similarity, and self-attribution. These scales, too, are presented on a disembodied Likert scale from 1 to 7. Additionally, we assessed the SoE several times during the VR experience using in-VR scales. We used the same scales for each assessment but adapted them to address either the embodied self-avatar, the embodied swap avatar, or the de-embodied self-avatar. We covered each of the dimensions of the VBO and VBO+ with one in-VR scale directly derived from these. All in-VR scales were presented on a scale from 0 (no agreement) to 10 (maximal agreement).

4.3.2 Interoceptive Awareness. To assess the trait of interoceptive awareness in advance, we used the Multidimensional Assessment of Interoceptive Awareness - Version 2 (MAIA) [48]. It comprises 37 items on the eight dimensions: noticing, non-distracting, not-worrying, attention regulation, emotional awareness, self-regulation,

[6] https://www.mcm.uni-wuerzburg.de/forschung/ethikkommission/

Figure 5: Exemplary participant's point of view before during the swap (from left to right).

body listening, and trusting. The scales are presented on a 6-point Likert scale from 0 to 5. We assessed the state of interoceptive awareness several times during the VR experience before and after the body swap, using in-VR scales as presented by Döllinger et al. [22]. These scales included noticing external signals (noticing external), noticing internal signals (noticing internal), body listening, attention regulation, and visual attention (preference of visual signals over other signals). Again, all in-VR scales were presented on a scale ranging from 1 to 10. Finally, we assessed the state of interoceptive awareness using the "body" dimensions of the State Mindfulness Scale (SMS) [70]. It comprises six items on a 5-point Likert scale ranging from 1 to 5. The SMS and the in-VR scales partially overlap. Thus, to ensure data economy, we assessed the SMS only post-VR.

4.3.3 Self-Compassion. We assessed the participant's traits in self-compassion using the Self-Compassion Scale - Short Form (SCS) pre-VR [60]. It comprises 12 items in six dimensions: self-kindness, self-judgment, common humanity, isolation, mindfulness, and over-identification. The items are presented on a 5-point Likert scale from 1 to 5. We assessed the state of self-compassion during the experience both pre- and post-VR using the State Self-Compassion Scale - Short Form (SSCS) [56]. It comprises six items. The items are presented on a 5-point Likert scale from 1 to 5.

4.3.4 User Experience. We assessed presence by using the One Item Presence Score (OIPS) [10]. The item was presented several times in VR on a scale of 1 to 10. We used semi-structured qualitative interviews to assess participants' qualitative experiences during the different tasks. The questions included the experience of the personalized avatar, the experience of the swap avatar, and the sensations during and after the body swap. They further included an evaluation of the meditation, the interactivity, and the motivation to repeat the experience.

4.4 Tasks

4.4.1 Embodiment Task. Each time embodying a new avatar, the participant performed simple body movements in front of the virtual mirror (see Figure 3), a common method to evoke a SoE [79]. The movement tasks were derived from Waltemate et al. [79]. They target different body parts for about 20 sec each. Following audio instructions, the participant waved at their mirror image, walked in place, and moved their hips while raising their arms. During these tasks, they were instructed to look at their mirror image and avatar from 1pp.

4.4.2 Self-Compassion Meditation. The VR experience was constructed to resemble a self-compassion meditation. The meditation procedure was derived from the guided meditations "Compassionate Friend" which introduces a compassionate friend and a perspective taking task and "Loving-Kindness Meditation" presented by Neff [55] which includes a row of positive affirmations directed at oneself. Accordingly, the swap partner was introduced as a compassionate friend in the virtual scenario and the self-compassion meditation included positive affirmations which were repeatedly presented to the participant. These included "may you be safe", "may you be at peace", "may you be healthy", and "May you go through life with ease and well-being".

4.5 Procedure

Our evaluation followed a standardized experimental procedure illustrated in Figure 6. Each experimental session was accompanied by a primary experimenter, who guided the participant through the session, and an assistant experimenter, who supported the avatar creation and embodied the swap avatar and personalized avatar during the VR experience. The assistant experimenter was selected to match the participant's gender but did not equal the female or male swap avatar. Participants were informed upfront that a person who was not the primary experimenter would be their swap partner but were not introduced to them as their swap partner until after the experiment. An experimental session included three phases: pre-VR, in-VR, and post-VR. Pre-VR, the participant read the study information, consented to the data collection, and created a pseudonymization code. In a second step, they were guided to the Embodiment Lab of the HCI Group at the University of Würzburg to perform the body scan for avatar creation. Afterward, the participant returned to the VR laboratory and answered MAIA, SCS, and SSCS questionnaires.

Figure 1 overviews the in-VR phase. In VR, all instructions were given via pre-recorded audio sequences, and some were additionally displayed on the virtual whiteboard (see Section 3.2). In the introduction phase, neither an avatar nor a mirror was visible. The participant performed a short vision test by reading text on the whiteboard to ensure the HMD was put on correctly. In the next step, the body tracking and embodiment system was calibrated. The

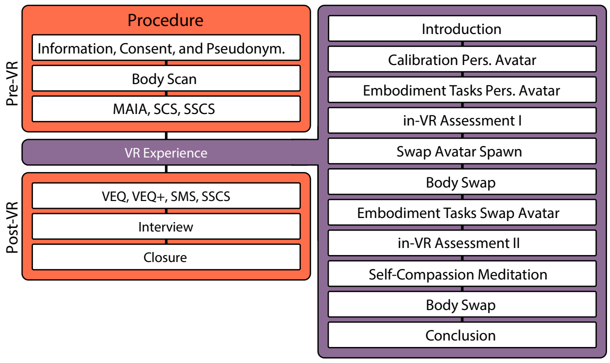

Figure 6: Overview of the experimental procedure.

personalized and the swap avatars were scaled to the participant's body height. The participant was instructed to perform a few idle movements and then stand still while facing the whiteboard.

To increase familiarity at the beginning of the in-VR phase, all participants started with embodying the personalized avatar. After the calibration, the participant's personalized embodied avatar and the virtual mirror appeared, and the whiteboard disappeared. To increase SoE, the participant performed the embodiment tasks (see Section 4.4.1). The whiteboard reappeared, and the participant answered the first in-VR scales about their interoceptive awareness and SoE toward their personalized avatar (in-VR assessment I). These in-VR scales were posed via audio instructions and the whiteboard, and the participant answered them verbally. Responses were noted by the experimenter. Following this, the footprints next to the circular marker appeared. The participant stepped on the footprints to their left. The swap partner was announced and introduced as a compassionate friend and appeared as the avatar (re-embody) or represented by two Knuckles (de-embody) in the position of the other footprints in front of the participant.

The participant initiated a first body swap (see Section 3.4). After the swap, the participant turned to the mirror and performed the embodiment tasks with their new appearance. They then turned to their personalized avatar and performed the self-compassion meditation (see Section 4.4.2). The whiteboard reappeared, and the participant was asked about their in-VR interoceptive awareness and in-VR SoE towards their personalized avatar and the swap avatar (in-VR assessment II). The participant then initiated a second body swap to return to their personalized avatar. The VR experience finished with a short scan of their bodily experience. Overall, the participant spent M = 23.40 min in VR. After putting down the VR equipment, the participant performed a second HCT and answered SSCS, SMS, UEQ, and Demographics questionnaires. Finally, the main experimenter performed the interview. The experimental session lasted M = 104.00 min.

5 RESULTS

5.1 Quantitative Results

5.1.1 Analysis. We calculated all analyses using R, including the packages *nlme*, *rstatix*, *report*. For plots, we used the package *ggplot2* and *ggpubr*. To analyze the effects of the swap (pre vs. post body swap) and the condition (de-embody vs. re-embody) on our in-VR measures (RQ 1.1, 1.2, 2.1, 2.2) and pre- and post-VR comparisons (RQ 3.1, 3.2), we fitted linear mixed models (estimated using REML and nlminb optimizer) to predict the respective dependent variable (formula: $dependent\ variable \sim swap\ (pre - post) \times condition$). The models included the participant id as random effect (formula: $1|id$). We report the t-values of individual comparisons within these mixed models. For analyses including only the condition (RQ 1.3, SoE toward the swap avatar), we calculated t-tests for independent groups. For the comparison between personalized and swap avatar (RQ 1.3), we calculated t-tests for paired groups. To analyze the relationship between SoE and self-related processes (RQ 1.4), we calculated simple linear regression models (formula:

Table 1: Descriptive results of pre-VR measures

		Overall	re-embody	de-embody
	Range	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Trait Interoceptive Awareness				
MAIA Attention regulation	[0–5]	2.91 (0.63)	2.74 (0.56)	3.07 (0.67)
MAIA Body listening	[0–5]	2.75 (0.79)	2.63 (0.62)	2.87 (0.95)
MAIA Emotional awareness	[0–5]	3.44 (0.90)	3.46 (1.01)	3.42 (0.83)
MAIA Self regulation	[0–5]	2.64 (0.86)	2.67 (0.99)	2.60 (0.77)
MAIA Non-distracting	[0–5]	2.84 (0.59)	3.10 (0.49)	2.58 (0.59)
MAIA Noticing	[0–5]	3.46 (0.66)	3.48 (0.58)	3.45 (0.76)
MAIA Not-worrying	[0–5]	2.70 (0.44)	2.94 (0.23)	2.46 (0.48)
MAIA Trusting	[0–5]	3.85 (0.74)	3.60 (0.89)	4.10 (0.47)
Self-Compassion				
SCS Self-judgement	[1–5]	2.58 (1.09)	3.00 (1.08)	2.15 (0.97)
SCS Self-kindness	[1–5]	3.25 (0.64)	3.15 (0.53)	3.35 (0.75)
SCS Common humanity	[1–5]	3.35 (0.99)	3.40 (0.97)	3.30 (1.06)
SCS Isolation	[1–5]	2.85 (1.05)	3.30 (1.06)	2.40 (0.88)
SCS Mindfulness	[1–5]	3.98 (0.75)	3.80 (0.71)	4.15 (0.78)
SCS Over-identification	[1–5]	3.28 (0.80)	3.60 (0.57)	2.95 (0.90)
SSCS	[1–5]	2.89 (0.38)	2.87 (0.23)	2.92 (0.50)

Table 2: Descriptive results of post-VR measures

		Overall	re-embody	de-embody
	Range	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
State Interoceptive Awareness				
SMS Body	[1–5]	3.29 (0.68)	3.40 (0.55)	3.18 (0.80)
Self Compassion				
SSCS	[1–5]	2.87 (0.41)	2.87 (0.27)	2.87 (0.53)
Sense of Embodiment (SoE)				
VEQ VBO	[1–7]	3.60 (1.53)	4.08 (1.61)	3.12 (1.37)
VEQ Agency	[1–7]	4.94 (1.34)	5.08 (1.21)	4.80 (1.52)
VEQ Change	[1–7]	3.34 (1.48)	3.02 (1.10)	3.65 (1.79)
VEQ+ Similarity	[1–7]	5.20 (0.98)	5.50 (1.03)	4.90 (0.88)
VEQ+ Location	[1–7]	3.76 (1.36)	4.05 (1.69)	3.48 (0.93)
VEQ+ Attribution	[1–7]	3.71 (1.67)	3.92 (2.04)	3.50 (1.26)

Table 3: Descriptive results of the in-VR measures

			Overall		de-embody		re-embody	
			pre swap	post swap	pre swap	post swap	pre swap	post swap
		Range	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Interoceptive Awareness	Noticing External	[1–10]	3.60 (2.26)	3.90 (2.34)	4.5 (2.68)	4.7 (2.58)	2.7 (1.34)	3.1 (1.85)
	Noticing Internal	[1–10]	5.90 (2.13)	6.15 (2.18)	6.3 (2.26)	6.5 (2.37)	5.5 (2.01)	5.8 (2.04)
	Body Listening	[1–10]	5.55 (2.46)	5.60 (2.21)	5.0 (2.71)	5.4 (2.55)	6.1 (2.18)	5.8 (1.93)
	Attention Regulation	[1–10]	6.65 (2.13)	5.95 (2.19)	6.2 (2.70)	6.1 (2.69)	7.1 (1.37)	5.8 (1.69)
	Visual Attention	[1–10]	6.85 (1.63)	5.90 (2.02)	7.2 (1.93)	5.7 (1.89)	6.5 (1.27)	6.1 (2.23)
SoE personalized avatar	in-VR VBO	[1–10]	4.50 (1.96)	4.75 (2.27)	5.0 (1.89)	4.9 (2.42)	4.0 (2.00)	4.6 (2.22)
	in-VR Agency	[1–10]	5.00 (2.29)	3.45 (2.11)	5.2 (2.20)	3.7 (2.16)	4.8 (2.49)	3.2 (2.15)
	in-VR Change	[1–10]	4.30 (1.95)	4.50 (2.26)	4.9 (2.13)	4.7 (2.11)	3.7 (1.64)	4.3 (2.50)
	in-VR Self-Similarity	[1–10]	6.55 (1.73)	6.20 (1.82)	7.1 (1.66)	5.9 (2.23)	6.0 (1.70)	6.5 (1.35)
	in-VR Self-Attribution	[1–10]	5.35 (2.11)	5.30 (2.11)	5.6 (2.17)	5.3 (2.21)	5.1 (2.13)	5.3 (2.11)
	in-VR Self-Location	[1–10]	3.45 (2.09)	2.80 (1.74)	4.0 (2.11)	3.2 (1.81)	2.9 (2.02)	2.4 (1.65)
SoE swap avatar	in-VR VBO	[1–10]	–	2.80 (2.07)	–	2.6 (2.41)	–	3.0 (1.76)
	in-VR Agency	[1–10]	–	3.45 (2.44)	–	1.7 (1.06)	–	5.2 (2.15)
	in-VR Change	[1–10]	–	4.45 (3.36)	–	3.0 (2.98)	–	5.9 (3.21)
	in-VR Self-Similarity	[1–10]	–	2.80 (2.09)	–	2.7 (2.41)	–	2.9 (1.85)
	in-VR Self-Attribution	[1–10]	–	2.80 (2.12)	–	2.5 (2.27)	–	3.1 (2.02)
	in-VR Self-Location	[1–10]	–	2.65 (1.84)	–	2.1 (1.37)	–	3.2 (2.15)
Sense of Presence		[1–10]	5.5 (1.79)	5.45 (2.28)	5.9 (1.60)	5.2 (2.62)	5.1 (1.97)	5.7 (2.00)

$self\text{-}reported\ process \sim SoE$), using the post-VR measures SMS Body, SSCS, VEQ, and VEQ+. All models were tested against an alpha of .05. The descriptive results of the pre-VR assessments on interoceptive awareness and self-compassion can be found in Table 1. The descriptive results of the post-VR assessments on SoE, interoceptive awareness and self-compassion can be found in Table 2. The descriptive results of the in-VR assessments on SoE and interoceptive awareness can be found in Table 3.

5.1.2 *Effects on Avatar Perception.*

SoE toward the Personalized Avatar. The swap negatively affected (RQ 1.1) on in-VR Agency, $\beta = -1.50,\ 95\%\ CI[-2.94, -0.06]$, $t(18) = -2.18,\ p = .042$, and on in-VR Self-Similarity, $\beta = -1.20$, $95\%\ CI[-2.14, -0.26]$, $t(18) = -2.68,\ p = .015$ (see Figure 7). We did not find a significant effect on in-VR VBO, $\beta = -0.10,\ 95\%\ CI[-1.60, 1.40]$, $t(18) = -0.14,\ p = 0.890$, Change, $\beta = -0.20, 95\%\ CI[-1.97, 1.57]$, $t(18) = -0.24,\ p = 0.815$, Self-Attribution, $\beta = -0.30,\ 95\%\ CI[-1.18, 0.58]$, $t(18) = -0.71,\ p = 0.484$, or Self-Location, $\beta = -0.80$, $95\%\ CI[-1.77, 0.17]$, $t(18) = -1.74,\ p = .099$.

Regarding RQ1.2, we did not find an effect of our condition on our in-VR SoE scales. We found neither an effect on in-VR VBO, $\beta = -1.00,\ 95\%\ CI[-3.01, 1.01]$, $t(18) = -1.04,\ p = .311$, Agency, $\beta = -0.40,\ 95\%\ CI[-2.52, 1.72]$, $t(18) = -0.40,\ p = .696$, Change, $\beta = -1.20,\ 95\%\ CI[-3.19, 0.79]$, $t(18) = -1.27,\ p = .221$, Self-Location, $\beta = -1.10,\ 95\%\ CI[-2.89, 0.69], t(18) = -1.29,\ p = .213$, Self-Similarity, $beta = -1.10,\ 95\%\ CI[-2.76, 0.56]$, $t(18) = -1.39$, $p = 0.181$, or Self-Attribution, $\beta = -0.50,\ 95\%\ CI[-2.53, 1.53]$, $t(18) = -0.52,\ p = .611$.

SoE toward the Swap Avatar. Regarding the SoE toward the swap avatar, our in-VR measures (RQ 1.3) revealed a significant effect of the condition on in-VR Agency, $\beta = 3.50,\ 95\%CI[1.91, 5.09]$, $t(18) = 4.62,\ p < .001$. We did not find a significant effect of condition on in-VR VBO, $\beta = 0.40,\ 95\%CI[-1.59, 2.39]$, $t(18) = 0.42,\ p = 0.677$, in-VR Change, $\beta = 2.90,\ 95\%CI[-0.01, 5.81]$, $t(18) = 2.09,\ p = 0.051$, in-VR Self-Similarity, $\beta = 0.20,\ 95\%CI[-1.82, 2.22]$, $t(18) = 0.21,\ p = 0.837$, in-VR Self-Location, $\beta = 1.10,\ 95\%CI[-0.59, 2.79]$, $t(18) = 1.36,\ p = 0.189$, or in-VR Self-Attribution, $\beta = 0.60, 95\%CI[-1.42, 2.62], t(18) = 0.62, p = 0.541$. In addition, participants reported significantly higher in-VR VBO, $t(19) = -2.78,\ p = .012,\ 95\%\ CI[-3.42, -0.482]$, Self-Similarity, $t(19) = -5.63,\ p < .001,\ 95\%\ CI[-4.66, -2.14]$, and Self-Attribution, $t(19) = -4.39, p < .001,\ 95\%\ CI[-3.69, -1.31]$, toward their personalized avatar from 3pp than toward the embodied swap-avatar (see Figure 8). Here, we did not find a significant effect regarding Agency, $t(19) < .01,\ p > .999,\ 95\%\ CI[-1.38, 1.38]$, Change, $t(19) = -0.06,\ p = .953,\ 95\%\ CI[-1.80, 1.70]$, or Self-Location, $t(19) = -0.27,\ p = .788,\ 95\%\ CI[-1.30, 1.00]$. Finally, we found higher Agency ratings for the visible swap avatar than the personalized avatar in the re-embody condition, $t(9) = 3.46,\ p = .007,\ 95\%\ CI[0.69, 3.31]$.

5.1.3 *Relationship between SoE and Self-Related Processes.*

Regarding the relationship between SoE and interoceptive awareness (RQ 1.4), our regression models revealed a positive relationship between VEQ VBO toward the personalized avatar and SMS Body, $R^2_{adj} = 0.24,\ F(1, 18) = 7.08,\ p = .016$, between VEQ Agency and SMS Body, $R^2_{adj} = 0.56,\ F(1, 18) = 25.63,\ p < .001$, and between VEQ Change and SMS Body, $R^2_{adj} = 0.32,\ F(1, 18) = 9.89,\ p = .006$ (see Figure 9). We did not find a significant relationship between VEQ+ Similarity and SMS Body, $R^2_{adj} < 0.01,\ F(1, 18) = 1.04,\ p = .320$, between VEQ+ Location and SMS Body, $R^2_{adj} = 0.11,\ F(1, 18) = 3.30,\ p = .086$, or VEQ Attribution and SMS Body, $R^2_{adj} < 0.01,\ F(1, 18) = 1.07,\ p = .315$.

Regarding self-compassion and SoE toward the personalized avatar, we did not find any significant relationship, neither for

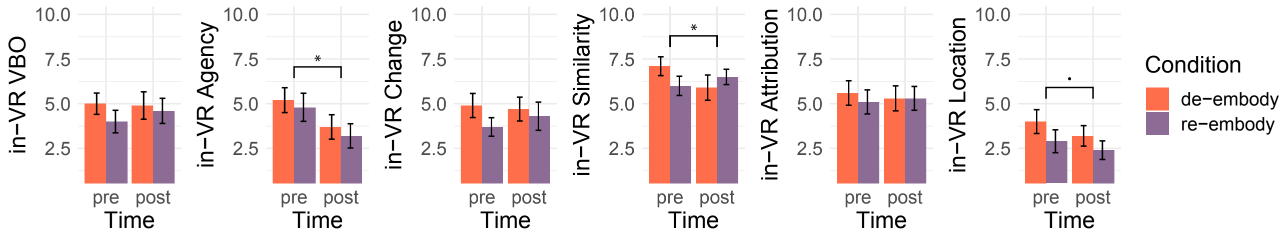

Figure 7: Results of the in-VR measures for SoE toward the personalized avatar ('·' $p < .1$; '∗' $p < .05$).

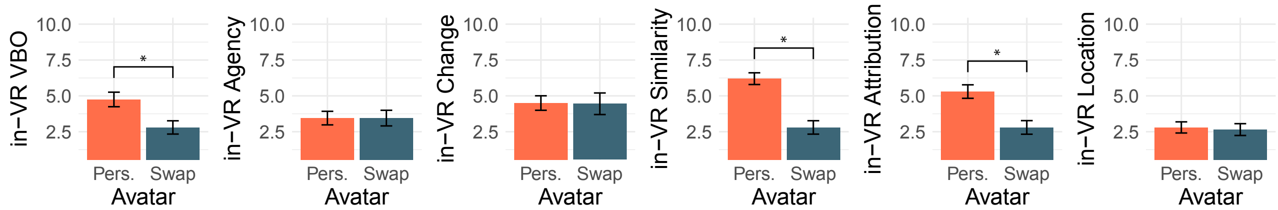

Figure 8: Comparison between the 3pp personalized avatar and the 1pp swap avatar after the swap (both conditions; '∗' $p < .05$; Pers. = personalized avatar, Swap = swap avatar).

VEQ VBO, $R^2_{adj} = 0.07$, $F(1, 18) = 2.52$, $p = .130$, VEQ Agency, $R^2_{adj} = 0.10$, $F(1, 18) = 3.15$, $p = 0.092$, VEQ Change, $R^2_{adj} = 0.06$, $F(1, 18) = 2.11$, $p = .164$, VEQ+ Similarity, $R^2_{adj} = -0.04$, $F(1, 18) = 0.22$, $p = .643$, VEQ+ Location, $R^2_{adj} = -0.02$, $F(1, 18) = 0.63$, $p = .439$, nor VEQ+ Attribution, $R^2_{adj} = 0.09$, $F(1, 18) = 2.98$, $p = .101$.

5.1.4 Effects on Self-Related Processes.

Interoceptive Awareness. Regarding RQ 2.1 and RQ 2.2 regarding the effects of the swap and our conditions on interoceptive awareness, we found the following. In VR, we found a significant positive effect of the swap on Body Listening, $\beta = 1.50$, $95\% CI[0.11, 2.89]$, $t(18) = 2.27$, $p = .036$, and a negative effect on Visual Attention, $\beta = -1.50$, $95\% CI[-2.78, -0.22]$, $t(18) = -2.46$, $p = .024$ (see Figure 10). Participants reported increased body listening and decreased focus on visual signals after the swap. We did not find a swap effect on Noticing External, $\beta = -0.30$, $95\%\ CI[-1.18, 0.58]$, $t(18) = -0.71$, $p = 0.484$, Noticing Internal, $\beta = 0.20$, $95\%\ CI[-0.79, 1.19]$, $t(18) = 0.43$, $p = 0.675$, and Attention Regulation, $\beta = -0.10$, $95\%\ CI[-1.15, 0.95]$, $t(18) = -0.20$, $p = 0.844$.

We did not find an effect of our conditions on Noticing External, $\beta = -1.80$, $95\%\ CI[-3.85, 0.25]$, $t(18) = -1.84$, $p = .082$, Noticing Internal, $\beta = -0.80$, $95\%\ CI[-2.85, 1.25]$, $t(18) = -0.82$, $p = .422$, Body Listening, $\beta = 1.10$, $95\%\ CI[-1.10, 3.30]$, $t(18) = 1.05$, $p = .307$, Attention Regulation, $\beta = 0.90$, $95\%\ CI[-1.16, 2.96]$, $t(18) = 0.92$, $p = .371$, or Visual Attention, $\beta = -0.70$, $95\%\ CI[-2.45, 1.05]$, $t(18) = -0.84$, $p = .412$. Post-VR, we did not find a significant effect of the condition on SMS Body, $t(15.94) = 0.70$, $p = .492$.

Self-Compassion. Regarding self-compassion (RQ 3.1 and 3.2), we did not find an effect of the swap, $\beta = -2.45e-15$, $95\%\ CI\ [-0.12, 0.12]$, $t(18) = -4.19e-14$, $p > .999$, nor of condition, $\beta = 0.05$, $95\%\ CI[-0.33, 0.43]$, $t(18) = 0.28$, $p = .786$, on the SSCS.

5.2 Qualitative Results and User Experience

5.2.1 Analysis. To analyze the qualitative data, we applied a summarizing content analysis [47] and rated the valence of each statement (positive, negative, or neutral). Two team members performed the analysis separately and then merged category by category. In the following, we present the results of this analysis regarding the user experience of the two avatars, the body swap and the meditation. Finally, we added some suggestions from the participants on design ideas for interactive tasks.

5.2.2 User Experience of the Avatars.

Experience of the Personalized Avatar. Before the swap, most participants reported positive affect toward their personalized avatar (11× positive, 4× negative). However, especially in the de-embody condition, an adverse change in mood occurred after the swap (10×). Participants reasoned the avatar seemed eerier from the new perspective or that it was eerie not to be able to control it: "Yes, it [the perception of my avatar] had changed. It felt more uncomfortable, more eerie than before. Not having control over the avatar is creepy." [participant 14]. Others perceived no change in mood (5×) or even perceived the personalized avatar more positively after the swap (4×), stating that it was "quite cool to look at oneself from the outside" [participant 12]. Twelve participants positively highlighted the appearance of the avatar, focusing on having a lower body (3×), a high similarity and realism (7×), and the realistic appearance of the avatar's clothes (2×). Further, two participants highlighted the

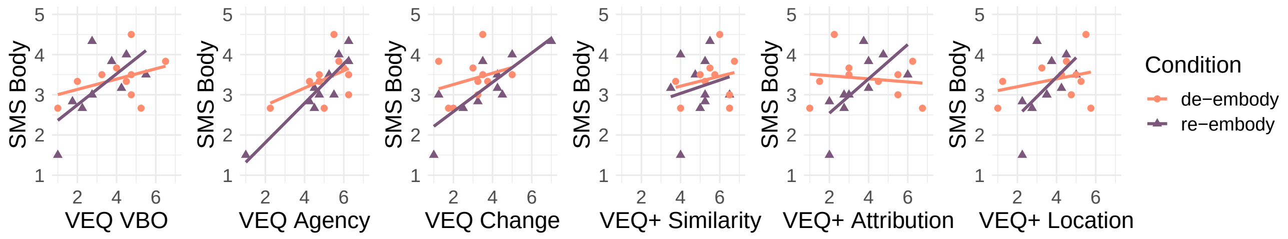

Figure 9: Relationship between SoE and interoceptive awareness ('∗' $p < .05$).

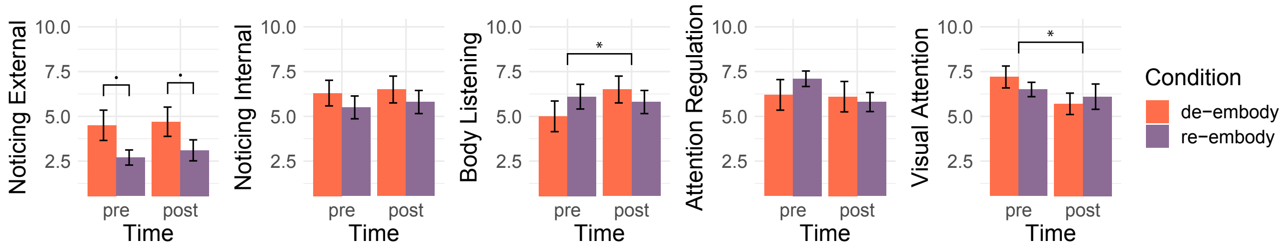

Figure 10: Results of the in-VR measures for interoceptive awareness ('·' $p < .1$; '∗' $p < .05$).

hand tracking, and two stated that they enjoyed seeing themselves from a new perspective. However, participants also gave a critical review of the avatar's realism. Four disliked the non-personalized hands of the avatars. Eleven stated inaccuracies in the appearance of the avatar's face, including their eyes (4×) or eye color (3×), their overall facial structures (2×), or their mouth (2×). One participant disliked the appearance of the avatar's pants. Five participants did not associate with their avatar's body posture (2×).

Experience of the Swap Avatar. Concerning the swap avatar, half of the participants initially expressed neutral feelings (10×). In line with our expectations, the two conditions differed here. In re-embody, some participants expressed positive feelings (3×), e.g., stating: "It was familiar as if a brother or good friend was standing next to me" [participant 17]. In de-embody, some participants were unpleasantly touched (3×) or confused (4×) because the invisibility of the swap partner did not correspond to their expectations: "It was weird because it wasn't a person but nothing" [participant 2]. After the swap, this surprise effect dissipated. Many participants still felt neutral toward the swap avatar (9×, 4 of them in re-embody, 5 in de-embody). However, in both groups, negative feelings towards the swap avatar arose (8×, 4 in each condition). Participants reasoned that it felt "strange" and that there was a difference in SoE compared to the personalized avatar. Only a few participants interpreted the swap avatar as positive after the swap (3×). Participant 19 stated: "I felt good, more comfortable than in my own avatar, you don't have to compare to reality. I am in VR, I am free".

5.2.3 User Experience of the Body Swap.

Experience of the General Perceptive Shift. The body swap interaction was rated mostly neutrally (11×, 5 in re-embody, 6 in de-embody) or positively (7×, 4 in re-embody, 3 in de-embody). Only two participants reported a negative experience. Participant 20 reasoned: "I didn't feel comfortable in my own avatar and even less so in someone else's, you couldn't identify with it at all".

Ten participants reported (6 in re-embody, 3 in de-embody) that the swap did not trigger any feeling of awe, reasoning that they would have expected more of it. However, eight participants rated the swap astounding, exciting, or "cool". Participant 3 explained: "[I felt like] 'Wow' because I've never seen myself from the outside before". Participant 9 stated: "It's amazing that this is possible. I didn't think my avatar would be so detailed". Ten participants expected the experience to change with repeated exposure regarding future use. Participant 18 stated: "You would probably become better at self-reflection and positive thinking".

Specifications of the Current Technology. The blackening of the display during the swap mainly was perceived as positive (10×) or neutral (3×) and interpreted as a relaxing pause between tasks. However, some participants found it disturbing (3×) or too long (4×). The physical handshake to trigger the body swap was reviewed critically. One participant liked the physical handshake: "I felt the hand and had a point of contact, so it was more realistic and better than if the body swap had happened suddenly" [participant 3]. However, seven participants reported ambivalent feelings, either disliking the indirectness of the controllers (3×) or the mixture of virtual and physical signals (4×), stating, e.g.: "It was interesting to touch another real person in VR. But you realized that there was a discrepancy between VR and reality" [participant 18].

5.2.4 User Experience of the Meditation Task.

Some participants reported engaging well with the audio-guided self-compassion meditation (7×, 5 in re-embody, 2 in de-embody). They liked its content (6×), especially the pre-formulated sentences and positive affirmations (5×) and the adaptation of sentences over time (1×). They further liked the execution of the meditation (5×), the concept of looking at their avatar during the meditation (3×), the voice of the instructor (1×), and that there was little distraction in the virtual world (1×). Three participants liked the effect of the meditation, as they experienced it as relaxing and calming.

However, others could not concentrate on the meditation (11×, 3 in re-embody, 8 in de-embody). Participant 2 stated: "It was strange to address [the affirmations] to me on the one hand and to the avatar on the other. A normal meditation where I still am myself would have been easier". Some participants had issues with the execution of the meditation (5×). Some felt insecure during the meditation as they did not know whether they should enunciate the affirmations (1×) or felt the urge to close their eyes to focus on the meditation and were unsure whether it was allowed (1×). Others disliked the frequency of repeating the affirmations (3×), rating them as too often, too fast, or too intrusive. One participant found the virtual environment not suitable for meditation. Regarding the meditation content, two participants found the affirmations weirdly worded.

5.2.5 *Ideas and Suggestions for Future Developments.*

Virtual and Human Swap Partners. Participants expressed diverse preferences regarding the design of the swap avatar, grouped into visibility, anthropomorphism, self-similarity, and familiarity. Four participants addressed the visibility of the swap avatar. While three preferred an invisible partner, one preferred to swap with a visible avatar. Seven participants discussed anthropomorphism. Two stated that the avatars should be designed even more realistically: "It would be better if the virtual aspect wasn't so present and the avatars were more human. Overall, just more realistic would be better" [participant 18]. However, four participants suggested deviations from realism, using animals (1×), fantasy or mythical creatures (3×), or more inconspicuously, with shadow figures (1×) as swap avatars. Six participants stressed the importance of similarity between the swap avatar and the user, stating, e.g., it should be "Similar to me, in appearance and character, so I can best identify and feel comfortable" [participant 8]. Specifically, some were concerned about gender (2×) or age (1×). In contrast, one participant suggested using a swap avatar distinct to the user in gender, appearance, weight, and height. Finally, commenting on familiarity, some participants preferred swapping with a familiar avatar (3×) or a famous person (1×). Others preferred an unfamiliar swap avatar. Finally, four participants stated that the appearance of the swap partner did not matter to them.

Participants answered diversely when asked whether they would allow another person to control their personalized avatar in the future. A majority stated no restrictions (14×). Others emphasized the importance of familiarity with the other person (5×), varying between "only someone I trust" (2×), "only people I know and like" (1×), and "only friends or family" (2×). Participant 18 stated they would rather not have anyone embody their personalized avatar, at least not if they were not there themselves.

Interactive Tasks. Participants suggested various alternative tasks to perform with their de-embodied avatars. A large part of the suggestions focused on joint physical activities, with the avatar not necessarily being the main focus of the activity (16×). These included exploring novel environments (3×), sports or games activities (4×), more active movements (5×), or going out to eat together (2×). Other suggestions focused on the avatar itself. For example, participants suggested talking to the avatar (4×) or having the opportunity to walk around it and look at it from all sides (5×). Furthermore, participants emphasized using activities only possible in VR (1×). One participant noted that engaging in an interactive exercise would be easier if they had a visible swap avatar. Finally, four participants stated they did not want to interact with their personalized avatar or had no idea what to do with it.

6 DISCUSSION

We presented a multi-user embodiment system enabling users to embody personalized and generic virtual avatars and exchange perspectives. Our evaluation results bring new insights into the SoE toward personalized avatars (RQ 1.1-1.3). Leaving the 1pp of a personalized avatar, participants reported reduced feelings of agency or self-location but not of the more appearance-based dimensions of SoE or VBO. These variables were still rated higher toward the personalized 3pp avatar than a generic 1pp avatar. Moreover, they were positively associated with interoceptive awareness (RQ 1.4). We further showed that while our intervention did not notably impact self-compassion, the virtual body swap not necessarily negatively affected self-related processes (RQ2.1-3.2). In contrast, we found a slight pre-post increase in body listening and a shift from virtual to bodily experiences (swap effect).

6.1 Leaving First-Person Perspective

In our experiment, leaving the 1pp of one's personalized avatar reduced the SoE over it. However, when taking a closer look at the dimensions of SoE, it becomes apparent that we must differentiate between the dimensions of SoE. Participants reported a reduction in dimensions related to the position and behavior of the avatar, with a significant effect on agency and a tendency on self-location. However, they did not report a reduction in the identification with the avatar, including self-attribution, change, or VBO. This result indicates a reduction of bottom-up SoE [42]. The continued strong top-down self-attribution and VBO highlight the necessity to distinguish between recognizing the shift in position and control and an actual higher-cognitive dis-embodiment effect.

Increasing the mental distance between an individual and their personalized avatar while maintaining self-attribution and VBO holds promise for various applications. Besides perspective-taking exercises, numerous psychotherapeutic approaches aim at creating self-distancing to support self-reflection [43]. Spatially distancing oneself from a virtual self could facilitate this mental disassociation. Further, embodying different personas during this self-distancing might offer benefits in mentally gaining new perspectives. For example, regarding individuals with eating or body image disorders, past research has shown that embodying and seeing different versions of one's personalized avatar can impact participants' body image and body weight perception [26, 72, 85]. Distancing oneself from one's avatar and embodying different perspectives on one's body could further enhance such interventions.

Interestingly, participants reported reduced self-similarity after the swap as they could see the personalized avatar's face from a closer distance. Regarding the qualitative answers, this closer perspective led to an increased feeling of uncanniness, as minor discrepancies between avatar and participant became more apparent. In addition to continuously improving the quality of personalized avatars, one solution would be to rely on more abstract avatars and thus reduce the risk of an uncanny valley effect [64]. However, such abstraction could limit applicability, as less detailed personalized avatars might reduce self-attribution [23, 62]. On a more superordinate level, it could be useful to identify the reasons behind discomfort and disassociation with one's personalized avatar. Some participants reported discomfort with the reduction of control over it after the swap. Revising the introduction and initiation of the body swap could increase comfort and strengthen the communication between the instructor and the participant.

6.2 After the Swap: Dis- or Multi-Embodiment?

Matching the findings regarding the personalized avatar, participants reported a lower SoE toward the swap avatar in some dimensions, while in others, they prioritized the swap avatar. This distinction differentiates between bottom-up SoE dimensions of avatar position and behavior and top-down dimensions of identification with the avatar and its appearance. Participants reported a higher sense of agency toward the swap avatar, at least in the re-embody condition. However, they did not prioritize the sense of self-location between the avatars. Regarding the identification with and appearance of the avatar, participants preferred their personalized avatar, reporting higher self-similarity, self-attribution, and VBO. Consequently, they distinguished clearly between the more top-down oriented identification with an avatar, which remains with the personalized avatar, and the assessment of their bottom-up perceptible positioning and agency in the virtual environment.

One could argue that participants felt multi- or dual-embodiment [36] effect regarding the bottom-up dimensions of SoE. While still identifying with their personalized representation, participants did not feel located stronger in one of the avatars than in the other. However, this also raises the question of whether a multi-embodiment effect can be reduced to its bottom-up processes. Even after the swap, participants identified with and felt VBO toward the personalized avatar, potentially given its appearance similarity. Previous studies used avatars matching each other's appearance [36], leading to a sense of dual embodiment through bottom-up stimulation. In other work, different-looking avatars affected SoE toward the swap avatar [66]. However, whether participants still felt associated with their primary avatar was not investigated. It remains questionable whether typical embodiment effects [82] are also effective in the presence of a non-embodied personalized avatar.

6.3 After the Swap: Self-Related Processes

We observed a positive correlation between post-VR measures of interoceptive awareness and SoE toward the personalized avatar, particularly in bottom-up oriented agency and the more top-down oriented VBO, change, and self-location. This outcome aligns with previous findings indicating a positive relationship between SoE and interoceptive awareness [15, 22, 23]. Our pre-post results on interoceptive awareness (swap effect) contradict the assumption that embodying avatars might reduce interoceptive awareness due to distraction or increased workload [23, 49]. In our study, subjects engaged simultaneously with two avatars, each evoking varying degrees of SoE. According to mental load theory, this dual load should reduce bodily sensations' processing capacity. However, our findings did not show such a reduction. Participants reported no significant swap effect in most interoceptive awareness ratings and a slight increase in body listening. Notably, they shifted focus from visual to bodily signals after the swap. Additionally, some participants enjoyed the meditation and anticipated positive effects over time. This result suggests that habituation or engaging playfully with the avatar could compensate for a potential initial decline of body awareness [22].

It is crucial to balance the technical capabilities, including real-time body swapping, with the original goals of increasing self-compassion. Unfortunately, we did not find a positive effect of our exercises on self-compassion, nor a difference between conditions. In general, the state self-compassion ratings in our sample were relatively high, indicating the possibility of a ceiling effect. Testing with a more diverse sample could help gain insights into the effects of virtual body swapping on self-compassion. On the other hand, participants reported having trouble focusing on the meditation. The novel experience of embodying a personalized avatar and the even more novel experience of body swapping might have suppressed the potential outcomes of our intervention. Finally, considering the main criticism of the self-compassion exercise, the rigidity and potentially unclear instructions of the meditation exercise stick out. While the meditation task was derived from an established self-compassion exercise [55], the VR implementation led to some confusion. Learning from our results, future interfaces should work on clarifying the direction of affirmations and individualizing their phrasing and pacing or creating more interactivity during the exposure.

6.4 Personalized Avatars as Social Actors

Regarding the perception of the personalized avatar, an exciting new question arises. Our research focused on perceiving the avatar as part of the self and the SoE. Self-identification persisted even when the avatar was left and participants embodied a second, uninvolved avatar. We take this as a positive indicator for future virtual out-of-body experiences [17]. Participants suggested various activities for their avatars, prompting a question whether the personalized avatar could be seen as a social partner. Given the external perspective on and external control of the avatar, some alienation between the user and avatar might occur, potentially causing a shift in self-location and agency. Future work will show whether this alienation leads to an experience of the avatar as a social presence [57].

Further, our results form a basis for future work regarding the choice of swap avatar. In earlier studies, the swap avatar representing an authority figure by its role as a therapist increased the positive effects of a self-counseling task compared to a personalized avatar [58, 66]. Compared to that, we created swap avatars matching the peer group of most of our participants, framed them as compassionate friends without suggesting authority, and compared them to an invisible swap partner. Except for agency, we found no differences between these conditions regarding SoE. Additionally, we received mixed feedback regarding the experience of not having a 1pp avatar after the swap. Participants expressed only a few remarks about the swap avatars besides not feeling as embodied in them as in the personalized avatar. This may have contributed to the lack of an effect on self-compassion. The effects of the previous studies are likely due to an underlying Proteus effect. To create a Proteus effect, an avatar must elicit a stereotypical association, such as Freud as a good counselor [58] or Einstein as a mathematical genius [6]. To focus on the personalized avatar, we used peers as swap avatars that potentially did not trigger strong stereotypes. However, given the potentials of the Proteus effect, creating swap avatars with a stronger association with intervention goals, such as compassion or empathy, might be a key factor in designing a virtual self-compassion intervention.

6.5 Future Work: Designing Virtual Perspective Shifts in Mind-Body Interventions

While our results do not answer all questions on the perception of virtual avatars and self-related processes in virtual body-swapping, they offer some insights for future research. Considering the design space of a virtual perspective change out of one's personalized avatar, various settings can be adjusted. In the following, we discuss requirements, challenges, and open questions regarding the appearance and behavior of different design elements across different moments of the experience.

6.5.1 The Personalized Avatar. In our scenario, photorealistic personalized representations of participants served as avatars. Past work highlights a positive impact of realism and personalization on SoE [52], yet it remains unclear whether this poses a risk for self-related processes [23]. However, to stimulate self-related processes, we see personalization as a possible opportunity. Participants highly identified with their avatar even when placed outside of it. Beyond appearance, the avatar's body language post-body swap may be pivotal. Creating similarities or deviations between participant behavior and avatar movements could be an exciting tool to impact self-identification or self-related processing, as body language affects the perception of compassion [5]. Controlling for possible uncanny valley effects [40], we see great potential for future investigations into how changes in the appearance or behavior of the avatar affect self-perception.

6.5.2 The Design of the Swap Avatar. Past research has shown great application potential, especially concerning the swap avatar's appearance. By swapping with a mentor [58] or changing into a childlike avatar [27], participants experienced support in their self-reflection. The suggestions of our participants show that the preferences regarding the swap avatar's appearance can be very individual. As mentioned, we opted for peers as swap avatars, not aiming at a Proteus effect but a focus on the personalized avatar. Besides that, the choice of our visible swap avatars and our human swap partners may have impacted our results. First, we intentionally limited our selection of swap avatars to two that were gender-matched to the participants but not further individualized. Second, we ensured the participants did not know the swap avatars before the experience. Studies of avatar individualization have shown their relevance in eliciting VBO [81] while critically evaluating the importance of considering user preferences [30], and effects on self-related processes such as body awareness [23]. Expanding these findings considering swap avatars and familiarity could be the next step in furthering the knowledge about the effects of avatar appearance on user experience.

6.5.3 Behind the Scenes: The Swap Partner. A body swap scenario involves a user, their current avatar, their swap avatar, and the unit controlling the swap avatar. Our participants differed in their preferences regarding who could embody and control their personalized avatars. Some mentioned allowing only a trusted person or no one. This raises the question of who might be a suitable partner behind the swap avatar. In our scenario, the swap partner was an assistant experimenter sharing the physical space with the participant. This created a co-embodiment situation in which subjects continued to feel associated with their personalized avatar while another person could view and control it from 1pp. Alternatives are imaginable. One option involves a swap agent with computer-controlled animations instead of a human-embodied swap avatar. Using a swap agent could offer increased situational control, which can be particularly advantageous in phobia or anxiety [67]. Computer-animating the personalized avatar facilitates adapting its body language to the user. A second option could involve not animating the avatar currently not embodied by the user. Besides further increasing control, this option would allow for a focus on the body without the effect of possibly unfamiliar body language.

Regarding a human swap partner, their relationship with the participant and their correspondence with the swap avatar raise the potential for future work. Some participants expressed the preference for swapping with someone familiar. The next step in intervention development could be to investigate how swapping with a familiar partner might affect the perception of the body swap. Additionally, it might be relevant to elaborate on whether familiarity with the swap avatar or the person controlling it is dominant in affecting the body swap experience. Since our participants expressed very individual preferences and fears toward the swap partner, future work should investigate how the swap partner affects the person's social and self-related processes.

6.5.4 The Design Space of the Swap. We used a handshake gesture to initiate the body swap, framing it as a swap even when the partner was invisible. While a handshake might be appropriate in some cultures, others may prefer alternative consensual gestures. Additionally, different framings are possible depending on the appearance and the use of a human or computer-controlled swap avatar. For example, stepping out of 1pp might be more beneficial in some situations. It would allow complete control over the speed of leaving 1pp and the perspective taken on. Further, it would prevent giving up control to another person embodying one's avatar. Again, especially for individuals dealing with anxiety or body image issues, increasing control over the situation could be beneficial [67]. In other situations, a targeted swap with another person could be preferable. As indicated by the participant's comments on potential swap partners, a body swap, compared to a simple perspective change, might raise the interaction to a new level. Swapping bodies allows participants to work with their bodies while creating real social interaction. Therefore, adapting to the respective necessities of different therapeutic or non-therapeutic situations is crucial.

Similarly, the swap initiation can be presented variously. Our participants' feedback mainly focused on the duration of the blackening between the swap and the indirect touch via the hand controllers. Future work could elaborate more deeply on which interactions benefit different use cases.

6.5.5 *Interactive Self-Compassion.*

Finally, another design element of the swap scenario is the post-swap exercises. While some subjects welcomed the quiet meditation in our design, others found it challenging to engage with, and we did not find a positive impact on self-compassion. Participants suggested post-swap exercises, predominantly involving shared physical activities or social interaction with the personalized avatar, aligning to prior work [58]. Further, participants' opinions varied regarding the verbal task instructions. Future work could investigate how different exercises and interactions benefit self-related processes in mind-body interventions and how these can be implemented.

6.5.6 *Risk Factors.*

In this initial evaluation of our prototype with healthy participants, some concerns emerged that merit attention in future work. Some participants expressed concern about who might experience their personalized avatar from 1pp. These concerns spotlight an issue regarding intimacy in virtual spaces. It is crucial to investigate whether allowing someone else to control an individual's personalized avatar is perceived as intimate. A virtual body swap might not inherently invade intimate space [38], given the absence of physical proximity from 1pp. Nevertheless, the experience of a third-party embodiment could affect the perceived intimacy or cause a loss of control over one's bodily depiction. A second concern expressed by participants was discomfort with embodying another character while their personalized avatar coexisted in the same virtual space. Again, future work must probe whether this scenario triggers adverse emotions and how to counteract them. Thirdly, some participants experienced an uncanny valley effect after the body swap, perceiving a reduced self-similarity between themselves and the avatar. This finding could be due to the novel perspective but also to the design of the avatars. Further investigation is necessary to avoid this effect in future implementations.

6.5.7 *Individualization.*

In summary, diverse and sometimes conflicting preferences and concerns were evident among participants regarding various design elements, be it the personalized avatar, the swap avatar, the swap partner, or the interaction. While self-related processes can be considered overarching for mind-body interventions [12], addressing individuals' distinct needs is crucial. Hence, future work should aim to identify and incorporate respective target groups' specific needs and vulnerabilities into the design of virtual body swaps or other mind-body-oriented virtual self-encounters.

6.6 Limitations

In addition to the potential social presence effects and lack of control regarding the similarity between our participants and the swap avatars mentioned above, we want to point out a few limitations.

In this study, all participants started by embodying the personalized avatar. This sequence could have impacted our findings, considering that the order in which different avatar types are embodied can affect how users perceive them [21]. We opted for this design to make it easy for participants to familiarize themselves with the virtual environment. A reasonable alternative for future studies could be to use a balanced design with participants either embodying their personalized or the respective swap avatar first. That way, the "compassionate friend" would be represented by either the personalized or the swap avatar. As prior work has shown, the identity of an avatar can determine the efficacy of avatar-mediated interventions [58]. Thus, providing insights into whether this is the case for self-compassion settings could be the next step in illustrating the effect of avatar identity on therapy-relevant outcomes.

In addition, while we explored various dimensions of SoE, we did not include a behavioral measure of SoE. Typically, methods like a virtual threat are used to measure VBO objectively [37]. While integrating a threat measure would have raised additional ethical concerns in our study, there is another reason for its exclusion. Adding a threat could affect how users empathize with their avatar, potentially biasing the outcomes of a self-compassion task. Nonetheless, it would be a good opportunity for future work to close this gap and determine how participants react visually to their de-embodied, personalized avatars being threatened.

Finally, our results are limited concerning our sample. We tested with a relatively small sample size, allowing extensive interviews after the experience but preventing the calculation of interaction or moderating effects between dependent variables. Particularly in the interaction between SoE and interoceptive awareness, investigating with a larger sample would have been interesting to determine whether the SoE plays an additional role in interoception compared to the swap avatar. Additionally, our sample was relatively homogeneous, consisting of young, healthy students with limited VR experience. All participants confirmed being comfortable with another person controlling their personalized avatar. Our data might be limited here, as we do not know how people with a stronger sense of intimacy or a lower self-compassion would respond to our system. However, our study marks the initial evaluation of our system. Consequently, concerning the potential risks associated with body-swapping, our findings represent a crucial initial stride toward future research involving more vulnerable demographics.

7 CONCLUSION

We present a virtual body-swapping system that allows multiple users to embody their personalized photorealistic avatars and to switch perspectives with other users in real-time. In our evaluation with 20 participants, we address the effect of a virtual body swap on the sense of virtual embodiment (SoE) toward one's personalized and swap avatar. We further connect this SoE to other self-related processes during the experience, including interoceptive awareness and self-compassion. Our results show that, while bottom-up processes of SoE pass over to the new avatar, the top-down self-identification remains with the personalized avatar even after the body swap. We further could show that while self-compassion remained unaffected, participants' interoceptive awareness was slightly increased after the body swap. Finally, we define a set of affordances for future research and design in the context of body swap-based virtual mind-body interventions. Virtual body swap experiences can be an innovative milestone for all interventions that work with perspective change. Our work sets an important stepping stone for the future design of such systems.

ACKNOWLEDGMENTS

This research has been funded by the German Federal Ministry of Education and Research (16SV8219, 16SV8223 and 16SV8225) and by the German Federal Ministry of Labour and Social Affairs (DKI.00.00030.21). We thank Lena Holderrieth and Julian Knepel for their assistance in implementing the prototype and the students of our MCS project course for supporting the study. We thank Matthias Beck, Lena Holderrieth, and Theresa Schell for supporting figure creation. Erik Wolf gratefully acknowledges a Meta Research PhD Fellowship.

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7 Exploring Agent-User Personality Similarity and Dissimilarity for Virtual Reality Psychotherapy

Döllinger, N., Topel, J., Botsch, M., Wienrich, C., Latoschik, M. E., & Lugrin, J.- L. (2024). Exploring agent-user personality similarity and dissimilarity for virtual reality psychotherapy. *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 424–427. doi: 10.1109/VRW62533.2024.00082

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Author Contributions

Nina Döllinger contributed to the conceptualization of the experimental design, supervised the development and data collection, performed the analysis, and took the lead in writing the manuscript. Jessica Topel developed the Unreal application, performed the data collection. Mario Botsch provided the avatar reconstruction framework. Carolin Wienrich and Marc Erich Latoschik supervised the project. Jean-Luc Lugrin contributed to the conceptualization of the experimental design and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

Exploring Agent-User Personality Similarity and Dissimilarity for Virtual Reality Psychotherapy

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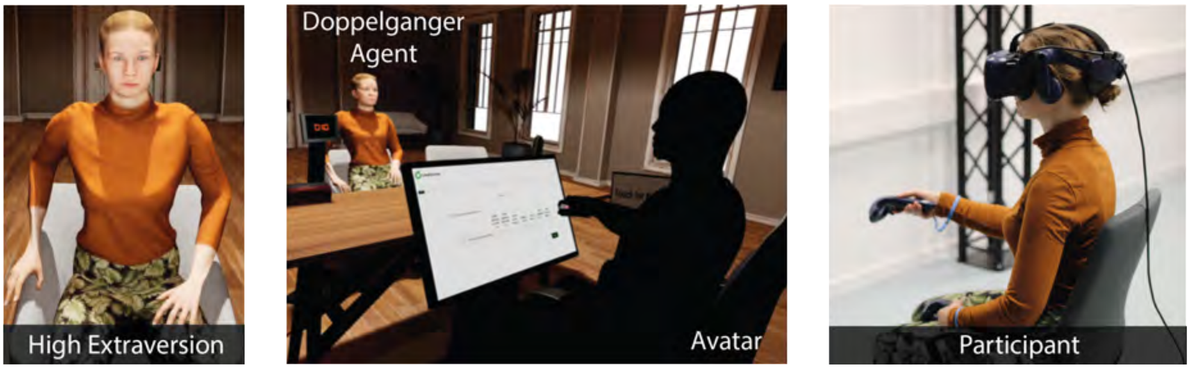

Figure 1: An exemplary participant's Doppelganger animated to show high extraversion (left), the experimental situation including the Doppelganger and the participant's avatar (center), and the participant controlling the avatar's movements (right).

Abstract

Imaginary self-encounters are a common approach in psychotherapy. Recent virtual reality advancements enable innovative approaches to enhanced self-encounters using photorealistic personalized Doppelgangers (DG). Yet, next to appearance, similarity in body language could be a great driver of self-identification with a DG or a generic agent. One cost-efficient and time-saving approach could be personality-enhanced animations. We present a pilot study evaluating the effects of personality-enhanced body language in DGs and generic agents. Eleven participants evaluated a *Photorealistic DG* and a *Generic Agent*, animated in a seated position to simulate four personality types: *Low* and *High Extraversion* and *Low* and *High Emotional Stability*. Participants rated the agents' personalities and their self-identification with them. We found an overall positive relationship between a calculated personality similarity score, self-attribution, and perceived behavior-similarity. Perceived appearance-similarity was affected by personality similarity only in generic agents, indicating the potential of body language to provoke a feeling of similarity even in dissimilar-appearing agents.

Keywords: Virtual reality, personality, body language, agents, self-identification, animation.

Index Terms: Human-centered computing—Virtual reality;

1 Introduction

Self-reflection to increase self-compassion, self-esteem, or self-regulation is a common tool in psychotherapeutic interventions. Virtual reality (VR) takes these methods to a new level by introducing photorealistic personalized virtual humans using full-body 3D scanners (e.g., [21]). Such virtual Doppelgangers (DGs [16]) have a high appearance similarity to the user and can be used as embodied self-avatars or as agents (autonomous computer-controlled entities [10]). However, dissimilar body language might break this virtual DG perception/illusion and affect the efficiency of the psychotherapy. Animating agents to have body language similar to a user without expensive motion capture sessions remains challenging. Recently, a new method was proposed to modify agent animations based on personality traits [13], which have been shown to be connected with body movements [18]. Adapting both appearance and body language (dis-)similarity could open novel ways to create therapeutic scenarios and evaluate virtual human perception. However, how such animations affect the user's perception of and identification with DGs is unclear.

To address this, we conducted a preliminary study comparing the effects of personality-enhanced body language and appearance dissimilarity on personality ratings and self-identification with agents (s. Fig. 1 for an overview). Participants rate the personality of a *Photorealistic DG* and a *Generic Agent*, animated to match the personality traits of *High Extraversion (HE)*, *Low Extraversion (LE)*, *High Emotional Stability (HS)*, or *Low Emotional Stability (LS)*. Our contribution is threefold. (1) We expand a system to create body language (dis-)similarities between users and anthropomorphic agents. (2) We outline a study design to examine the effects of personality-enhanced animations on self-identification. (3) We present preliminary results showcasing the potential of personality-enhanced animations.

2 Related Work

There are several possibilities for creating virtual humans with varying degrees of appearance dissimilarity. Cheymol et al. [4] offer an overview of characteristics defining such dissimilarities at either an atomic or a holistic level. Striving for a maximized appearance similarity, recent developments in photorealistic virtual human personalization aim for a close congruence at a relatively efficient time and cost [2], fostering high self-identification [14]. Opting for agents over embodied self-avatars adds a new dimension to creating (dis-)similarities. Creating body language similarity might facilitate plausibility and increase the identification with an agent on a subtle level [12]. On the other hand, body language dissimilarity holds vast potential for virtual self-encounters. Exemplifying adjust-

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ments in body language could help modify self-perception and adapt self-expression. It could further facilitate self-distancing [11], an essential step in therapeutic self-reflection. Conversely, inappropriate body language representations could lead to a disassociation with the DG or indulge the risk of negative experiences [9].

2.1 Body Language in Agents: Adapting Personalities

In the design of agent animation systems, personality and its effect on body language are a frequent topic. Neff et al. [15] found that self-adapting movements in agents reduce emotional stability ratings, while higher gesture rates and specific edits in gesture performance increased extraversion ratings. Smith and Neff [17] investigated the effects of hand position, movement speed, or arm swivel on agent personality ratings. They found significant differences for all personality traits. In a comprehensive framework, Sonlu et al. [18] linked the Big Five personality traits (extraversion, agreeableness, conscientiousness, emotional stability, and openness) with body language across dialog and speech, facial expressions, and body movements. They note that openness and conscientiousness require dialogue and voice for effective portrayal, while extraversion, agreeableness, and neuroticism suit systems without speech. Based on this framework, Lugrin et al. [13] implemented a non-verbal personality behavior model for VR agent animation, allowing the expression of individual Big Five traits. They found a distinction in ratings between high and low extraversion and high and low emotional stability among desktop-presented generic agents. Our study adds to these results by elevating them to a VR environment and exploring how personality similarity or dissimilarity links to self-identification.

2.2 Agent Perception: The Role of Appearance

Being confronted with a DG agent potentially has not only positive effects. Compared to a generic virtual human with less appearance similarity, a DG might increase appearance-related self-consciousness, negatively affecting self-assessments [6]. The DG's appearance might thus trigger negative self-esteem by highlighting perceived shortcomings and accentuating the disparities between one's actual self and personal expectations [6], ultimately leading to an adverse change in self-esteem. Moreover, embodying personalized avatars, compared to generic ones, can lead to more eeriness and a withdrawal from physical sensations [5]. Using an agent with high body language similarity yet lacking any appearance similarity may be a solution to help maintain self-esteem and self-identification, ultimately enhancing the efficiency of a VR therapy tool. Participants may perceive self-identification with an agent that has an entirely different appearance but exhibits a high level of personality similarity through their body language [7]. Overall, it remains unknown how agent appearance and behavior integrate into a perception of similarity and self-identification and whether any combination of both can benefit psychotherapy relying on self-encounters in VR.

3 Methods

Our study outline includes a 2×4 within-subjects design. Our independent variables are appearance similarity (*Photorealistic DG* vs. *Generic Agent*) and personality-enhanced body language (*HE*, *LE*, *HS*, and *LS*). Fig. 2 shows an exemplary DG and a generic agent in postures from the four body language conditions. We expect a high level of appearance and personality similarity to induce a higher sense of self-identification between the user and an agent. We also hypothesize that agents with a low appearance similarity but a higher level of personality similarity will generate higher self-identification. We measure self-identification in terms of appearance-similarity, self-attribution, and behavior-similarity [7].

3.1 Personality-Enhanced Agent Animation System

We use a custom animation system for virtual humans with personality-specific body language, as introduced by Lugrin et

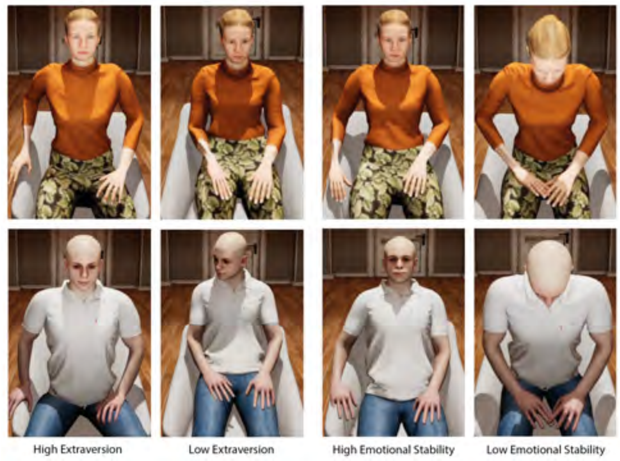

Figure 2: Exemplary doppelganger and the generic agent showing different personality-enhanced behavior animations.

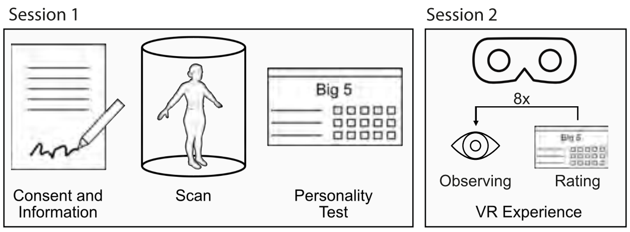

Figure 3: Overview of the experimental procedure. The period between session 1 and session 2 was five to seven days.

al. [13], which the authors provided for our use. This system features sitting animations representative of the four personality types in our study. We modified and adapted the system to our needs. In particular, we modified the gaze control mechanism. For HE, agents glance away briefly before returning their gaze to the user. For LE, we implemented the inverse behavior. Agents with this trait only look at the user's eyes for one second before shifting their gaze to a different target. Additionally, we developed a method to switch an agent's personality dynamically during the application and incorporated blinking animations to enhance realism and avoid an uncanny valley effect.

3.2 Agents Conditions

The study includes two types of agents consisting of virtual humans controlled by our personality animation system: a male agent from Adobe Mixamo characters, representing our *Generic Agent* condition, and the participant's DG, representing our *Photorealistic DG* condition (Fig. 2). The DGs are created in the local university's embodiment lab using a 3D photogrammetry full-body scanner. The resulting models are fully rigged and textured. To match our animation system's restrictions, we adjust them slightly in Blender. We parent the leg bones to the lowest spine bone and transfer the weight from the lowest spine bone to the middle spine bone to allow for better compatibility with the skeleton of the generic agent. To enhance the DGs' lifelike appearance, we change their eyes' UV mapping to align with Epic Games' MetaHuman's Eyes Material. As the skeleton of the Photorealistic DGs differs from that of the generic agents, we re-target the animations. We use a Control Rig created with the Unreal Engine's Control Rig Plugin.

3.3 Participant's Avatar

The virtual representation of a human body in VR plays a crucial role in shaping the overall experience and its impact on individuals. For instance, it increases presence [19] and plausibility [12] and reduces mental workload [20]. In addition, various therapeutic virtual self-encounters presuppose the embodiment of virtual humans that deviate from the patient in appearance [1, 16].

However, determining the ideal appearance for an avatar can be challenging, particularly when encountering a Doppelganger. To avoid potential effects of avatar appearance on the participants' self-perception and , thus, potentially on how they rate their DG, we designed a neutral avatar using a completely unlit texture on a standard human body shape (see Fig. 1, center). Previous studies have shown that users adapt their behavior to expectations and stereotypes associated with their avatar's appearance (Proteus effect [22]). In addition, people reliably associate what virtual humans wear (outfit color, design, and type) with their personality traits [3]. Our unlit avatar design aims to eliminate any potential influence of clothing, appearance or body shape on participants' self-perception and DG perception. The avatar is visible from a first-person perspective, matches the participants' seated position, and replicates their head, hand, and arm movements via an upper-body inverse kinematic. The length of the avatar's arms is adjusted to match the participant's arms during a fast calibration process at the start of the experiment.

3.4 Virtual Environment

The virtual scene comprises a simple room with a table, a clock, and two screens. A large touchscreen in front of the participant displays the questionnaire, and a smaller screen serves as a "next agent" button. A virtual chair marks the participant's position, similar to the physical chair they sit on during the experiment. The agents are positioned opposite the participant across the table (Fig. 1, center).

3.5 Technical Setup

The VR setup operates on Unreal Engine 4.27.2 and runs on a Windows 10 PC with an i7-9700K CPU, 32GB RAM, and an RTX 2080 Ti GPU. It utilizes an HTC Vive Pro HMD with 1140×1600 resolution per eye and a 90 Hz rate, along with four Lighthouses and two motion controllers for hand tracking. Surveys are conducted via LimeSurvey on a university PC (session 1) or through a web browser directly integrated into VR (session 2).

3.6 Measures

We assess personality using the Ten Item Personality Inventory (TIPI) [8] both for the personality of the participants and the agents. The TIPI consists of five dimensions matching the Big Five personality traits. It is assessed in ten items on a 7-point Likert scale from 1 (does not apply at all) to 7 (fully applies). In addition, we calculate a personality similarity score using the absolute value of the difference in personality ratings between participants and agents. We reversed the result and calculated a mean value including all TIPI dimensions, resulting in a range between 0 (no similarity) and 6 (maximum similarity).

To assess self-identification, we use three questions from the extended Virtual Embodiment Questionnaire VEQ+ [7]: (1) "The overall appearance of the virtual human was similar to me" (appearance-similarity, adapted from self-similarity), (2) "I could identify myself with the virtual human" (self-attribution), and (3) "I felt the virtual human was behaving as I would behave" (behavior-similarity, adapted from self-attribution). They are assessed on a 7-point Likert scale, from 1 (disagree strongly) to 7 (agree strongly).

3.7 Procedure

The study consists of two sessions (Fig. 3). Initially, participants consent, undergo a body scan for their digital double, and fill out a demographic survey and the TIPI on a PC. In the subsequent session, participants are seated in the lab and calibrate their avatar before evaluating it. They observe each agent for 30 seconds, then rate its personality and their self-identification with it, using in-VR on-screen questionnaires. The sequence of agent presentations, varying in appearance and personality body language, is randomized across two blocks.

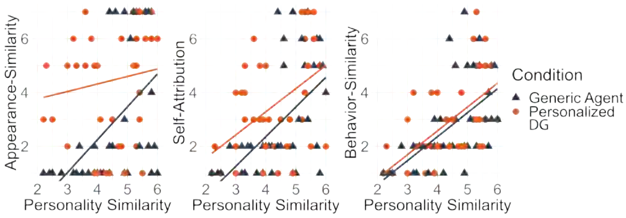

Figure 4: Relationship between personality similarity scores and self-identification ratings.

4 Preliminary Evaluation

For our pilot test, we recruited participants via the local university's study portal, with participants receiving course credits as compensation. Our exclusion criteria were (1) known photosensitivity, (2) uncompensated visual impairments, and (3) high simulator sickness prevalence. Fourteen undergraduate students participated. Three were excluded because of technical issues, resulting in 11 participants (9 female, 2 male) with a mean age of $M = 21.18, SD = 1.40$ years. Two participants had no experience with VR, eight had been in VR one to ten times, and one had been in VR more than 20 times. Four participants had prior experience with DGs.

Table 1 overviews our descriptive results. We calculated repeated measures correlations using the *R* package *rmcorr* to gain insight into a potential relationship between personality similarity and self-identification. On an alpha level of .05, we found a significant correlation between personality similarity and self-attribution, $r(76) = 0.44,\ p < .001,\ 95\%\ CI\ [0.24, 0.60]$, and between personality similarity and perceived behavior-similarity, $r(76) = 0.60,\ p < .001,\ 95\%\ CI\ [0.43, 0.72]$. We did not find a significant correlation between personality similarity and perceived appearance-similarity, $r(76) = 0.22, p = .057,\ 95\%\ CI\ [-0.01, 0.42]$. Fig. 4 gives an overview of the three variables.

Our preliminary results reveal intriguing first insights. First, they tend to confirm our expectations. We observed an overall positive relationship between personality similarity and a sense of behavior-similarity and self-attribution, suggesting the potential to affect self-identification in similar and dissimilar agents. Interestingly, on a descriptive note, the sense of appearance-similarity seems to correlate with personality similarity only when using generic agents (see Fig. 4, left). This result indicates stability in the sense of appearance-similarity of DGs. However, it hints at the potential to evoke a sense of appearance-similarity via body language even with agents with a dissimilar appearance. Further, on a descriptive level, participants seem to have recognized the four personality traits within both appearance conditions. Overall, our results indicate an effect of agent body language on self-identification and personality perception. This promising result shows the efficiency and potential of personality-enhanced animation systems. However, further data is necessary to validate these observations.

5 Conclusion

We introduced a personality-enhanced body language animation system as a novel approach for therapeutic VR self-encounters. We conducted a preliminary evaluation to investigate how simulating agents with similar or dissimilar personalities to participants affected

Table 1: Descriptive results. (HE = High Extraverison, LE = Low Extraversion, HS = High Emotional Stability, LS = Low Emotional Stability)

		Generic Agent				**Photorealistic DG**			
		HE	LE	HS	LS	HE	LE	HS	LS
		M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
TIPI Personality Rating	Extraversion	5.32 (1.62)	2.14 (0.81)	3.55 (1.59)	2.41 (1.20)	4.55 (1.42)	2.27 (1.23)	3.00 (1.45)	2.27 (0.93)
	Agreeableness	3.77 (1.37)	5.32 (0.75)	5.09 (1.34)	4.14 (1.19)	4.50 (1.64)	4.91 (1.46)	4.64 (1.94)	3.27 (1.17)
	Conscientiousness	5.05 (1.31)	4.36 (1.21)	4.91 (1.28)	3.82 (1.33)	5.68 (0.93)	4.64 (0.74)	4.95 (1.13)	4.14 (0.87)
	Emotional Stability	5.14 (1.38)	4.23 (0.98)	4.50 (1.75)	2.68 (1.19)	5.32 (0.96)	3.05 (1.17)	4.32 (1.44)	3.41 (1.53)
	Openness	4.27 (0.93)	3.55 (0.69)	4.32 (1.37)	3.50 (1.10)	4.41 (1.30)	3.27 (1.03)	3.82 (1.45)	3.05 (0.72)
Personality Similarity		4.84 (0.79)	4.37 (0.72)	4.67 (1.13)	3.76 (1.17)	5.16 (0.69)	4.01 (1.13)	4.44 (1.00)	3.68 (0.93)
Self-Identification	Self-Similarity	2.73 (2.76)	2.64 (2.38)	2.91 (2.66)	2.73 (2.57)	4.91 (1.70)	4.45 (1.75)	4.45 (2.30)	3.82 (2.27)
	Self-Attribution	3.00 (2.32)	2.45 (1.69)	3.36 (2.25)	2.45 (1.86)	4.18 (1.60)	3.45 (1.75)	3.91 (2.17)	2.73 (1.95)
	Behavior-Similarity	2.91 (1.70)	2.27 (1.10)	3.55 (1.92)	2.18 (1.33)	3.55 (1.29)	2.45 (1.21)	3.55 (2.02)	1.91 (0.83)

their perception of a virtual agent with the same appearance (Doppelganger) and a virtual agent with a different appearance. Our results indicate that personality-driven animations could be a powerful tool to affect agent perception by increasing or decreasing self-identification. Our future work will try to replicate our findings with a larger and more diverse sample, including a generic agent matching the gender, body type, and outfit of the participant.

Acknowledgments

This research was funded by the German Federal Ministry of Labour and Social Affairs [DKI.00.00030.21].

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List of Abbreviations

VR Virtual Reality

AR Augmented Reality

MR Mixed Reality

XR Virtual, Augmented, and Mixed Reality (VR, AR, MR; in short: XR)

UX User Experience

RQ Research Question

VEQ Virtual Embodiment Questionnaire

A In-VR Items to Assess the Sense of Embodiment

Sense of embodiment towards the corporeal/virtual body (Chapter 4)

body ownership	Es hat sich angefühlt, als ob der Körper den ich sah, mein Körper wäre.
agency	Die Bewegungen des Körpers den ich sah, wirkten, als wären sie meine Bewegungen.
change in body schema	Ich hatte das Gefühl, dass sich die Form oder Erscheinung meines eigenen Körpers verändert hat.

Sense of embodiment towards a virtual body perceived from first-person perspective (Chapters 5, 6)

body ownership	Die Bewegungen des Avatars wirkten als wären sie meine Bewegungen.
agency	Ich hatte das Gefühl, dass sich die Form oder Erscheinung meines physischen Körpers verändert hat.
change in body schema	Ich hatte das Gefühl, dass sich die Form oder Erscheinung meines physischen Körpers verändert hat.

Sense of embodiment towards a virtual body perceived from first-person perspective and in a virtual mirror while another, personalized avatar is visible in the same virtual room (Chapter 6)

body ownership	Es fühlt sich an, als ob das Spiegelbild mein Körper wäre.
agency	Die Bewegungen des Spiegelbilds wirken als wären sie meine Bewegungen.
change in body schema	Ich habe das Gefühl, dass sich die Form oder Erscheinung meines physischen Körpers verändert hat.
self-similarity	Ich habe das Gefühl, dass das Gesamterscheinungsbild des Spiegelbilds mir ähnlich ist.
self-identification	Ich habe das Gefühl, dass ich mich mit dem Spiegelbild identifizieren kann.
self-location	Ich habe das Gefühl, dass ich mich in dem Spiegelbild befinde.

Sense of embodiment towards a (personalized) avatar perceived from third-person perspective after a body swap (Chapter 6)

body ownership	Es fühlt sich an, als ob mein Gegenüber mein Körper wäre.
agency	Die Bewegungen meines Gegenübers wirken als wären sie meine Bewegungen.
change in body schema	Ich habe das Gefühl, dass sich die Form oder Erscheinung meines physischen Körpers verändert hat.
self-similarity	Ich habe das Gefühl, dass das Gesamterscheinungsbild meines Gegenübers mir ähnlich ist.
self-identification	Ich habe das Gefühl, dass ich mich mit meinem Gegenüber identifizieren kann.
self-location	Ich habe das Gefühl, dass ich mich in meinem Gegenüber befinde.

Self-Identification with a (personalized) avatar presented from third-person perspective (Chapter 7)

self-identification	Ich hatte das Gefühl, dass ich mich mit der virtuellen Person identifizieren konnte.
appearance-similarity	Das Aussehen der virtuellen Person erinnerte mich an mich selbst.
behavior-similarity	Ich hatte das Gefühl, dass die virtuelle Person sich so verhält, wie ich mich verhalten würde.

B In-VR Items to Assess Body Awareness

Noticing External	Ich bemerkte verschiedene Empfindungen, die durch meine Umgebung verursacht wurden (z. B. Hitze, Kühle, Wind im Gesicht).
Noticing Internal	Ich spürte physisch deutlich, was in meinem Körper vor sich ging.
Body Listening	Ich hörte auf das, was mein Körper mir sagte.
Attention Regulation	Es fiel mir leicht, die Aufmerksamkeit auf meinen Körper zu richten.
Visual Attention	Ich konzentrierte mich eher darauf, wie mein Körper aussah, als wie er sich fühlte.

C Instructions for Body Awareness Exercise: Standing Tasks of Basic Body Awareness Therapy Exercises

Es folgen nun einige Bewegungsübungen. Diese sind darauf ausgerichtet, deinen Körper intensiv wahrzunehmen. Es gibt dabei kein richtig oder falsch. Führe die Bewegungen so durch, dass du dich dabei wohlfühlst.

Stelle dich zunächst so hin, wie du normalerweise stehst. Wie erlebst du deine Haltung? Hast du das Gefühl, stabil zu stehen? Bist du angespannt oder entspannt?

[Pause]

Um in eine ausgeglichene Haltung zu finden, beginne mit der Wahrnehmung deiner Füße. Wie weit sind sie voneinander entfernt? Stehen sie eher abgewinkelt oder parallel? Ist dein Gewicht gleichmäßig auf beide Füße verteilt? Liegt dein Gewicht eher auf den Fersen oder auf den Fußballen?

[Pause]

Stelle nun deine Füße etwa hüftbreit auf. Um deine Balance zu finden, verlagere dein Gewicht ein paarmal nach vorne und nach hinten. Beobachte dabei, wie sich der Druck auf deine Fußsohle verändert und wie sich dein ganzer Körper anfühlt. Versuche dich so zu positionieren, dass dein Gewicht auf der Mitte deiner Füße liegt. Bei den meisten Menschen liegt dieser Schwerpunkt etwas weiter vorne, als wir es gewohnt sind. Verlagere anschließend dein Gewicht von links nach rechts, bis dein Gewicht auf beiden Beinen gleich verteilt ist.

[Pause]

Prüfe als nächstes die Stellung deiner Knie. Sind sie nach hinten gebogen oder nach vorne gebeugt? Spann deine Beine an, indem du sie etwas nach hinten drückst. Achte darauf, wie sich das anfühlt. Gib dann in den Knien nach; mach sie etwas weicher, sodass du sie leicht nach vorne und hinten bewegen kannst und die Beine leicht gebeugt sind.

[Pause]

Achte nun auf deine Hüfte. Schiebe dein Becken leicht nach vorn und spüre, was mit deinem Rumpf passiert. Bewege dann das Becken leicht nach hinten, sodass der Oberkörper nach vorn geneigt wird und die Hüftgelenke gebeugt sind. Finde zurück in eine mittlere Position des Beckens. Das Becken sollte, ebenso wie die Knie leicht gebeugt sein.

[Pause]

Richte als nächstes deine Aufmerksamkeit auf den Rumpf. Sind der Rücken und der Brustkorb angespannt oder entspannt? Ist die Haltung im Rumpf aufrecht oder gekrümmt? Wie hältst du deinen Kopf im Verhältnis zum Rumpf?

[Pause]

Auch hier suchen wir nach einer ausgewogenen Haltung. Richte deine Aufmerksamkeit zuerst auf die Krümmung der unteren Wirbelsäule. Eine leichte Krümmung ist hier normal, allerdings sollte es sich entspannt anfühlen. Bewege deine Hüfte leicht Vor und Zurück, um zu prüfen, ob die Krümmung zu sehr spannt, oder ob dein Rücken zusammensackt.

[Pause]

Spüre als nächstes in deinen Brustkorb und die Brustwirbelsäule. Spüre nach, wie sich der Brustkorb durch die Atmung hebt und senkt. Senke das Kinn leicht nach unten, sodass du eine Dehnung im Nacken spürst.

[Pause]

Nachdem du nun einen ausbalancierten Stand gefunden hast, fahre mit einigen aktiveren Bewegungen fort. Komme zurück in die Ausgangsposition und verlagere aus dieser Position dein Gewicht auf die Vorderfüße und hebe deine Fersen. Wippe ein paarmal auf und ab. Setze deine Fersen wieder auf den Boden. Beuge nun die Knie leicht nach vorne, allerdings nicht über die Fußspitzen hinaus. Um im Gleichgewicht zu bleiben, schiebe dein Becken leicht nach hinten und lehne dabei deinen Oberkörper etwas nach vorn. Arme und Brustkorb bleiben locker. Um den Nacken zu entspannen, kannst du deinen Blick gerne leicht nach unten senken. Drücke dich mit deinen Beinen zurück in die aufrechte Position. Wiederhole die Übung, indem du deine Knie wieder beugst und deinen Körper nach unten bewegst. Bleibe kurz in dieser Position, bevor du die Knie wieder streckst und in die Ausgangsposition zurückkommst. Lass deine Atmung so in die Bewegung einfließen, wie es sich am natürlichsten anfühlt.

Wiederhole die Übung so lange, bis die nächste Übung instruiert wird.

[Pause]

Komme nun zurück in die Ausgangsposition. Die nächste Übung besteht aus einer Rotation um deine Gleichgewichtslinie. Die Füße bleiben dabei im Boden verankert, die Arme hängen locker neben dem Körper. Drehe nun deinen Körper um deine Körperachse abwechselnd nach links und rechts, ähnlich wie bei einem Diskuswurf. Aktiviere dabei deinen kompletten Körper. Führe die Bewegung mit möglichst wenig Kraftaufwand durch und integriere deine Atmung in den Bewegungsrhythmus.

Wiederhole die Übung so lange, bis die nächste Übung instruiert wird.

[Pause]

Komm für die nächste Übung zurück in die stehende Ausgangsposition. In dieser Übung führst du eine Hebe- und Senkbewegung durch. Mit der Einatmung hebst du deine Arme nach vorn bis knapp unter Schulterhöhe und streckst die Knie. Mit der Ausatmung beugst du die Knie leicht und bewegst deine Arme wieder nach unten in Richtung Rumpf. Die Fersen bleiben dabei am Boden. Stelle dir beim Absenken der Arme vor, du würdest einen Ball unter Wasser drücken. Die Aufwärtsbewegung dient als Erholungsphase. Lass die Atmung in die Bewegung mit einfließen, sodass der Körper als Einheit wirkt.

Wiederhole die Übung so lange, bis die nächste Übung instruiert wird.

[Pause]

Für die letzte Übung komm zunächst zurück in deinen stabilen Stand. Stelle nun die Füße in eine Schrittstellung, der vordere Fuß zeigt nach vorn, der hintere zeigt ca. 45 Grad nach außen. Für ausreichend Stabilität sollten die Füße weiterhin etwa hüftbreit stehen. Die Knie bleiben auch in dieser Fußstellung leicht angewinkelt. Führe nun einige Gewichtsverlagerungen nach vorn und hinten durch, um die Stabilität der Schrittstellung zu prüfen. Richte deinen Blick nun nach vorne auf ein imaginäres Ziel und halte deine Hände vor deinem unteren Brustkorb nebeneinander. Die Handflächen zeigen dabei nach vorne. Verlagere nun dein Gewicht auf das vordere Bein und schiebe deine Hände aktiv nach vorne, als würdest du einen Gegenstand vor dir wegschieben. Führe deine Hände anschließend wieder zurück zu deiner Brust. Integriere deine Atmung in die Bewegung. Atme bei der Vorwärtsbewegung aus und bei der Rückwärtsbewegung ein. Deine Körpermitte bleibt dabei stabil.

Wiederhole die Übung so lange, bis die nächste Übung instruiert wird.

[Pause]

Wechsle nun die Position der Füße und wiederhole die Übung auf der anderen Seite. Integriere auch hier deine Atmung in die Übung.

Wiederhole die Übung so lange, bis die nächste Übung instruiert wird.

[Pause]

Stelle dich nun nochmal in die Ausgangsposition. Spüre die Bewegungsübungen für ein paar Atemzüge nach.

D Instructions for Self-Compassion Exercise: Meditation "Compassionate Friend"

Erlaube dir, deinem Gegenüber Wohlwollen und Freundlichkeit entgegenzubringen. Sieh dir dafür dein Gegenüber an und wiederhole im Stillen die folgenden Sätze: Mögest du sicher sein - Mögest du friedlich sein - Mögest du gesund sein - Mögest du mit Leichtigkeit und Wohlbefinden durchs Leben gehen.

Drehe dich nun nach rechts, sodass du dein virtuelles Abbild vor dir siehst. Erlaube dir, deinem Gegenüber Wohlwollen und Freundlichkeit entgegenzubringen. Sieh dir dafür dein Gegenüber an und wiederhole im Stillen die folgenden Sätze:

- Mögest du sicher sein
- Mögest du friedlich sein
- Mögest du gesund sein
- Mögest du mit Leichtigkeit und Wohlbefinden durchs Leben gehen

[Pause nach jedem Satz, Wiederholung der Sätze 2 mal]

Und wenn dein Gegenüber gerade eine schwere Zeit durchmacht, kannst du in jeden Satz ein "so gut wie möglich" hinzufügen. Wiederhole dies also im Stillen für dich selbst. Versuche, mit dem wirklichen, echten Gefühl der Fürsorge, der Besorgnis, der Güte in Kontakt zu kommen, das du für dein Gegenüber empfindest. Wenn deine Gedanken abschweifen, komm einfach zu den Sätzen zurück

- Mögest du sicher sein
- Mögest du friedlich sein
- Mögest du gesund sein
- Mögest du mit Leichtigkeit und Wohlbefinden durchs Leben gehen

[Pause nach jedem Satz]

Wenn du den Wunsch verspürst, die Formulierung der Sätze anzupassen, fühle dich frei dies zu tun.

Es ist nun an der Zeit, wieder in dein Gegenüber zurückzukehren. Sobald du dazu bereit bist, strecke deine Hand nach vorne aus, um seine Hand zu berühren.

List of Publications

E

First-Authored Papers

Döllinger, N., Mal, D., Keppler, S., Wolf, E., Botsch, M., Israel, J. H., Latoschik, M. E., & Wienrich, C. (2024). Virtual body swapping: A VR-based approach to embodied third-person self-processing in mind-body therapy. *Proceedings of the CHI Conference on Human Factors in Computing Systems*.

Döllinger, N., Beck, M., Wolf, E., Mal, D., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023b). "If it's not me it doesn't make a difference" – the impact of avatar personalization on user experience and body awareness in virtual reality. *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 483–492.

Döllinger, N., Wolf, E., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023). Are embodied avatars harmful to our self-experience? The impact of virtual embodiment on body awareness. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*.

Döllinger, N., Wolf, E., Mal, D., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022). Resize me! Exploring the user experience of embodied realistic modulatable avatars for body image intervention in virtual reality. *Frontiers in Virtual Reality*, *3*.

Döllinger, N., Wienrich, C., & Latoschik, M. E. (2021). Challenges and opportunities of immersive technologies for mindfulness meditation: A systematic review. *Frontiers in Virtual Reality*, *2*, 29.

Late Breaking Work/Workshop Papers/Posters

Döllinger, N., Topel, J., Botsch, M., Wienrich, C., Latoschik, M. E., & Lugrin, J.-L. (2024). Exploring agent-user personality similarity and dissimilarity for virtual reality psychotherapy. *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 424–427.

Döllinger, N., Göttfert, C., Wolf, E., Mal, D., Latoschik, M. E., & Wienrich, C. (2022). Analyzing eye tracking data in mirror exposure. *Proceedings of Mensch Und Computer 2022*, 513–517.

Döllinger, N., Wolf, E., Mal, D., Erdmannsdörfer, N., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022). Virtual reality for mind and body: Does the sense of embodiment towards a virtual body affect physical body awareness? *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*.

Döllinger, N., Wienrich, C., Wolf, E., Botsch, M., & Latoschik, M. E. (2019). ViTraS – virtual reality therapy by stimulation of modulated body image – project outline. *Mensch und Computer 2019 – Workshopband*, 606–611.

Co-Authored Full Papers, Short Papers, and Abstracts

Mal, D., Döllinger, N., Wolf, E., Wenninger, S., Botsch, M., Wienrich, C., & Latoschik, M. E. (2024). Am i the odd one? exploring (in)congruencies in the realism of avatars and virtual others in virtual reality [Preprint]. *arXiv*.

Mal, D., Wolf, E., Döllinger, N., Botsch, M., Wienrich, C., & Latoschik, M. E. (2024). From 2D-screens to VR: Exploring the effect of immersion on the plausibility of virtual humans. *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems*.

Wienrich, C., Vogt, S., Döllinger, N., & Obremski, D. (2024). Promoting eco-friendly behavior through virtual reality – implementation and evaluation of immersive feedback conditions of a virtual co2 calculator. *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*.

Fiedler, M. L., Wolf, E., Döllinger, N., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023). Embodiment and personalization for self-identification with virtual humans. *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 799–800.

Gemesi, K., Döllinger, N., Weinberger, N.-A., Wolf, E., Mal, D., Wienrich, C., Luck-Sikorski, C., Bader, E., & Holzapfel, C. (2023). Auswirkung von (virtuellen) Körperbildübungen auf das Ernährungsverhalten von Personen mit Adipositas – Ergebnisse der Vitras-Pilotstudie. *Adipositas – Ursachen, Folgeerkrankungen, Therapie*, *17*(03), S10–05.

Luck-Sikorski, C., Hochrein, R., Döllinger, N., Wienrich, C., Gemesi, K., Holzmann, S., Holzapfel, C., & Weinberger, N.-A. (2023). Digital communication and virtual reality for extending the behavioural treatment of obesity – the patients' perspective: Results of an online survey in germany. *BMC Medical Informatics and Decision Making*, *23*(1), 100.

Mal, D., Wolf, E., Döllinger, N., Wienrich, C., & Latoschik, M. E. (2023). The impact of avatar and environment congruence on plausibility, embodiment, presence, and the proteus effect in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, *29*(5), 2358–2368.

Gemesi, K., Holzmann, S. L., Hochrein, R., Döllinger, N., Wienrich, C., Weinberger, N.-A., Luck-Sikorski, C., & Holzapfel, C. (2022). Attitude of nutrition experts toward psychotherapy and virtual reality as part of obesity treatment—an online survey. *Frontiers in Psychiatry*, *13*.

Keppler, S., Döllinger, N., Wienrich, C., Latoschik, M. E., & Israel, J. H. (2022). Self-touch: An immersive interaction-technique to enhance body awareness. *i-com*, *21*(3), 329–337.

Mal, D., Wolf, E., Döllinger, N., Botsch, M., Wienrich, C., & Latoschik, M. E. (2022). Virtual human coherence and plausibility – Towards a validated scale. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 788–789.

Wolf, E., Döllinger, N., Mal, D., Wenninger, S., Bartl, A., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022). Does distance matter? embodiment and perception of personalized avatars in relation to the self-observation distance in virtual reality. *Frontiers in Virtual Reality*, *3*.

Wolf, E., Fiedler, M. L., Döllinger, N., Wienrich, C., & Latoschik, M. E. (2022). Exploring presence, avatar embodiment, and body perception with a holographic augmented reality mirror. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 350–359.

Wolf, E., Mal, D., Frohnapfel, V., Döllinger, N., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022). Plausibility and perception of personalized virtual humans between virtual and augmented reality. *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 489–498.

Wienrich, C., Döllinger, N., & Hein, R. (2021). Behavioral framework of immersive technologies (behavefit): How and why virtual reality can support behavioral change processes. *Frontiers in Virtual Reality*, *2*, 84.

Wolf, E., Merdan, N., Döllinger, N., Mal, D., Wienrich, C., Botsch, M., & Latoschik, M. E. (2021). The embodiment of photorealistic avatars influences female body weight perception in virtual reality. *2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 65–74.

Brandenburg, E., Ringel, O., Zimmermann, T., Döllinger, N., & Stark, R. (2020). Digital fitting instructions for further usage in product-lifecycle. *TESConf 2020 – 9th International Conference on Through-life Engineering Services*.

Wolf, E., Döllinger, N., Mal, D., Wienrich, C., Botsch, M., & Latoschik, M. E. (2020). Body weight perception of females using photorealistic avatars in virtual and augmented reality. *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 462–473.

Wienrich, C., Döllinger, N., Kock, S., & Gramann, K. (2019). User-centered extension of a locomotion typology: Movement-related sensory feedback and spatial learning. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 690–698.

Wienrich, C., Schindler, K., Döllinqer, N., Kock, S., & Traupe, O. (2018). Social presence and cooperation in large-scale multi-user virtual reality – the relevance of social interdependence for location-based environments. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 207–214.

Wienrich, C., Döllinger, N., Kock, S., Schindler, K., & Traupe, O. (2018). Assessing user experience in virtual reality – a comparison of different measurements. *Design, User Experience, and Usability: Theory and Practice: 7th International Conference, DUXU 2018, Held as Part of HCI International 2018, Las Vegas, NV, USA, July 15-20, 2018, Proceedings, Part I*, 573–589.

Brandenburg, E., Döllinger, N., Geiger, A., & Stark, R. (2017). Kognitive Modelle zur virtuellen Absicherung der mentalen Belastung bei Montagetätigkeiten. *DFX 2017: Proceedings of the 28th Symposium Design for X, 4-5 October 2017, Bamburg, Germany*, 25–36.

Weber, B., Hertkorn, K., Döllinger, N., & Kremer, P. (2013). Visuelle Assistenz bei telepräsenten Objektmanipulationen mit einem humanoiden Roboter. In M. Grandt & S. Schmerwitz (Eds.), *Tagungsband 55. fachausschusssitzung anthropotechnik*.

F List of Presentations

Paper Presentations

2024 ACM Conference on Human Factors in Computing Systems (CHI), Honolulu, USA

2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Sydney, Australia

2023 ACM Conference on Human Factors in Computing Systems (CHI), Hamburg, Germany

2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Tokyo, Japan

Invited Talks

2023 Deutscher Kongress für Psychosomatische Medizin und Psychotherapie. Topic of the talk: "Body Awareness and Mindfulness in Virtual Meditation"

2022 Adipositaskongress der Deutschen Adipositas-Gesellschaft (DAG). Topic of the talk: "How and Why Immersive Technologies Can Change Behavior – Virtual Reality in Body Image Therapy"

2019 Pictoplasma Conference & Festival Berlin. Topic of the talk: "Content versus Technology - Effect of Affordances on Human Perceptions and Reactions"

Workshop Presentations

2024 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Orlando, USA. 1st Workshop on Perception and Animation of Dissimilar AvatarS (PANDAS).

2023 ACM Conference on Human Factors in Computing Systems (CHI), Hamburg, Germany. Workgroup on Interactive Systems in Healthcare (WISH) Symposium.

2019 ACM Conference on Mensch und Computer (MuC), Hamburg, Germany. Workshop on Virtuelle und Augmentierte Realität für Gesundheit und Wohlbefinden.

Poster Presentations

2022 ACM Conference on Mensch und Computer (MuC), Darmstadt, Germany

2022 ACM Conference on Human Factors in Computing Systems (CHI), New Orleans, USA

Others

2024 Guest Talk @ University of Central Florida, Orlando FL, USA. Topic: "Replacing the Body in Embodiment - The Impact of Virtual Bodies on Interoceptive Awareness in VR"

2023 Technical Demonstration @ Würtual Reality XR Meeting, Würzburg, Germany. Topic: "Resize Me!"

2019 Guest Lecture @ Nihon University, Chiba, Japan. Topic: "Human-Computer-Interaction in Virtual Reality"

Colophon

This thesis was typeset with $\LaTeX\,2_\varepsilon$. It uses the *Clean Thesis* style developed by Ricardo Langner. The design of the *Clean Thesis* style is inspired by user guide documents from Apple Inc.

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