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The self in extended reality: How human factors shape self-environment interactions

Kumulative Dissertation
zur Erlangung des
Doktorgrades der Naturwissenschaften

25. Oktober 2023

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Acknowledgements

This journey started a long time ago. Not in my PhD, but somewhere in my master when I visited Durham University and became fascinated by embodiment, leading me to write a master thesis on embodiment in Katja Fiehler's team. I am thankful that I could now deepen my knowledge on this topic with this PhD project. Part of what made this journey so great and kept me motivated are the many colleagues I met during this time.

I would like to take the opportunity to thank Meaghan McManus, Yanina Tena Garcia, Petra Borovska, Marcel Linka, Max Broda, and so many more, for making my time in Giessen memorable and always being open to exchange new ideas. Especially I would like to thank:

- Katja Fiehler, for being my supervisor and letting me try something new by expanding into a new field of research.
- Harun Karimpur, for being my supervisor and friend. You gave me new ideas inspiring my work and life.
- Laurence Harris and his team, especially John Kim, for making my research visit at York University interesting, fun and educational.
- Immo Schütz, for his advice on all technological difficulties and peculiarities I encountered during my PhD.
- Elena Führer, for sharing an office with me and keeping me motivated to write on my thesis.
- Diana Kollenda and Bianca Baltaretu for proof reading my thesis.
- The research assistants for their help in collecting the data for my experiments.

I am thankful that I was so warmly welcomed to this special environment on the third floor in experimental psychology, allowing me grow as a scientist and person. Last but not least I would like to thank my family and friends who always supported me during this thesis project.

Abstract

The self is a pivotal point for interactions with the environment. Embodying what belongs to the self supports the perception of being a separate entity from the environment in which we feel present. Interacting with objects in this environment requires knowing the position of the self and the target objects in space. Although target objects can be encoded relative to the self (egocentric) or other objects (allocentric), motor plans for goal-directed movements are always expressed in egocentric coordinates. Thus, to understand 'self-environment' interactions, it is necessary to consider processes defining the self in conjunction with processes for encoding object positions in space.

The literature reviewed in the first study suggested that embodiment and presence are closely related. However, their relation is still ill-defined. This motivated me to introduce a new conceptual framework, the Implied Body Framework, which specifies the relation between embodiment and presence and also shows how actions in a virtual environment can influence both processes. The second study followed up on challenges related to investigating the subjective experience of the self. The results show that participants presented with the experimental procedures in an online experiment formed expectations matching the subjective ratings of participants in the actual virtual reality experiment. These expectations could bias participants to rate questionnaire items in line with the experimenter's hypotheses. The third study focused on the role of the self when interacting with objects in the environment. In this study, participants reproduced a configuration of balls presented in VR from memory. Manipulating participants' egocentric spatial position introduced errors when reproducing the relative ball positions, showing that allocentric spatial memory depended on the egocentric position of the self.

Together, these studies highlight the role of the self when interacting with the environment and the challenges associated with investigating self-related processes. This is not only relevant for interactions within the environment immediately surrounding the self, but also when using teleoperation systems to interact with objects remotely.

Contents

I Synopsis

1 Introduction

Imagine you are playing a virtual reality (VR) game. You use your virtual hands to grasp a key from a nearby book shelf and use it to open the door to escape the room. You might only realise upon finishing the game and taking off the headset that the experience in the virtual room was simulated and you are now back in the real world. This example shows that experiencing a virtual reality scenario can feel similar to the real world. We might experience the virtual avatar as our own body and feel as though we are in the virtual environment. Importantly, we are not a passive observer, but actively interact with the objects in this virtual environment.

We seldom pause to appreciate this close interplay between the self and the environment in the face of goal-directed actions. Different sensory information is integrated into a coherent body representation. This enables us to perceive ourselves as a separate entity within an environment. To interact with this environment, the position of the target object needs to be encoded and put into relation to the self. These two fundamental processes, i.e., discerning what belongs to the self and putting objects in the environment in relation to the self, need to be solved by the brain.

In this thesis, I present three studies investigating different aspect of 'self-environment' relations for goal-directed actions. I will first take a look at the processes constituting the feeling of being a self in an environment and then probe methodological challenges associated with investigating these subjective experiences. Finally, I will describe self-environment interactions by investigating the spatial relation between the self and the objects in the environment.

1.1 Discerning what belongs to the self

Embodiment is the process that constitutes a body representation by integrating bodily entities, resulting in a separation between the self and the environment. An external entity, e.g., a fake hand, can be embodied, if it is processed similar to the real body (part), e.g., the real hand (de Vignemont, 2011). Integrating sensory input from different sensory modalities might therefore be an essential process underlying embodiment (Chancel et al., 2022; Samad et al., 2015). This can be illustrated with the rubber hand illusion (RHI), commonly used to examine embodiment processes (e.g., Botvinick and Cohen, 1998; Chancel and Ehrsson, 2020; Longo et al., 2008).

In the RHI, participants see a brush stroking a rubber hand in front of them, while their real hand, hidden from view, is stroked synchronously (illusion condition) or asynchronously (control). Multisensory correlations between seen and felt brush strokes lead to the illusory feeling that the rubber hand belongs to the self (Botvinick and Cohen, 1998; Ehrsson et al., 2007). In this case, visual and tactile sensations are inferred to originate from the same source (Chancel et al., 2022), while contradicting proprioceptive information becomes adjusted to fit the percept of a rubber hand belonging to the self (Botvinick and Cohen, 1998; Samad et al., 2015). Embodying a bodily entity like a rubber hand or a virtual arm gives rise to the feeling of ownership, location, and agency, respectively describing the feeling of owning the embodied entity, of knowing where it is located in relation to the self, and of being in control of its actions (Kilteni et al., 2012). Embodying what belongs to the self distinguishes the self from the environment. It might thereby promote the feeling of being present in an environment.

The term presence emerged as telepresence from the field of teleoperation (Draper et al., 1998). Using a teleoperation system to operate a machine remotely, e.g., steering an unmanned vehicle, might even provoke a feeling of being at the remote site (Sheridan, 1992). Although presence is often seen as a key element in teleoperation (Draper et al., 1998; Hu et al., 2022), no coherently used conceptualisation of presence exists (Lee, 2004; Skarbez et al., 2017; Souza et al., 2021). To be present in an environment is frequently circumscribed as the feeling of 'being there' (Souza et al., 2021), making it a simple and wide spread description of presence. This is for example apparent in efforts to describe presence as consisting of 'being there' (place illusion) and perceiving events in the environment as real (plausibility). Within this approach, being able to interact within and having the environment react appropriately to one's self are important factors underlying the plausibility component of presence (Slater et al., 2022). This suggests that interacting with the environment might facilitate presence. However, interacting is clearly also relevant for embodiment.

Acting requires body movements that can be directed at the environment or the objects within it. The fact that we move our body can inform us on what belongs to ourselves. Respectively, the RHI can be induced by visuomotor correlations, e.g., by moving one's finger and seeing the finger of the rubber hand move accordingly (Abdulkarim et al., 2023; Kalckert and Ehrsson, 2014a). Compared to the classic visuotactile RHI, active movements tolerate less spatial offset between a real and fake hand (Kalckert and Ehrsson, 2014b). To minimise the multisensory conflict arising from the spatial offset between a real and rubber hand, the brain initiates motor activity toward the embodied entity (Lanillos et al., 2021). Accordingly, a mismatch between the movements of participants and an embodied virtual avatar biases participants' movements toward the avatar's movements (Burin et al., 2019). Together, this suggests a close connection between self-related processes and the actions performed within an environment. To use these generated insights in practical applications, e.g., as design principles to improve teleoperation devices (Nostadt et al., 2020), it is important to consider methodological challenges which often hinder comparability of different studies and contribute to inconsistent results (Riemer et al., 2019).

1.2 Challenges when investigating the self

Assessing the subjective experiences of the self is a challenging task which is also visible in the way researchers attempt to measure them. Questionnaire measures are easy to use and cost efficient, which might promote their widespread use (Riemer et al., 2019; Souza et al., 2021). However, they are prone to bias (Cronbach, 1946) and it is sometimes unclear if they capture the intended processes (Slater, 2004). If participants rate their subjective feelings on a fixed set of questionnaire items, it is possible that they categorised other experiences to make sense of the questionnaire items. In theory, those experiences could therefore be constructed when rating the questionnaire items (Slater, 2004). This challenges the isolated use of questionnaires.

Objective measures like proprioceptive drift and physiological responses (Box 1) are a useful addition to subjective measures, although it is important to consider that both cannot necessarily be used interchangeably. Findings that objective measures do not always match with participants' questionnaire ratings (Eftekharifar et al., 2020; Holle et al., 2011; Qu et al., 2021), might result from experimental manipulations influencing subjective and objective measures differently. For example, experiencing a virtual pit without motion parallax reduced subjective presence ratings, but increased the skin conductance response because the environment is more frightening due to missing depth cues (Eftekharifar et al., 2020). A more systematic investigation showed that while the synchrony of virtual and real hand movements affected participants' ownership ratings, no such effect was observed for proprioceptive drift. In addition, subjective and objective measures were uncorrelated (Ma et al., 2021), suggesting that the two measures capture different aspects of embodiment (Ma et al., 2021; Qu et al., 2021). Thus, objective measures cannot replace subjective measures, but they are an important addition to more fully understand the measured processes. However, it is an open question how well

Box 1 | Objective measures of embodiment and presence

Proprioceptive drift is typically assessed in the RHI by introducing a spatial offset between participants' real and rubber hand and letting participants point toward the felt location of the real hand, which is hidden from view. The indicated location is typically biased toward the rubber hand, taken as an indicator that participants embodied the rubber hand (Botvinick and Cohen, 1998; Kalckert and Ehrsson, 2014a).

Physiological measures like skin conductance or heart rate rely on participants' physiological response to threatening stimuli, e.g., a virtual pit or a knife threatening a rubber hand. The logic is that if participants show a physiological response to the threatening event, they embodied the fake body (part) or felt present in the virtual environment (Meehan et al., 2002; Petkova and Ehrsson, 2008; Slater, Spanlang, Sanchez-Vives, and Blanke, 2010).

these measures separate between related constructs.

Physiological measures in response to threat have been used for embodiment and presence research alike (Meehan et al., 2002; Petkova and Ehrsson, 2008; Slater, Spanlang, Sanchez-Vives, and Blanke, 2010). This indicates that these measures might not separate between embodiment and presence or that the two processes share some commonalities. In the past, studies investigated embodiment and presence mostly separately (Nostadt et al., 2020), therefore concealing possible relations between both processes. Conceptionally, embodiment and presence research have in common that it can be difficult to hide the purpose of the study from participants, especially when relying on questionnaires. This makes them prone to the same biases.

Letting participants rate their experiences on a questionnaire could inform them about the rationale of the experiment and might consequently bias their responses (Reader, 2022). The phenomenon that participants form expectations about the experiment, which might be in line with the research hypotheses, is known as demand characteristics (Corneille and Lush, 2023). If participants correctly guess the research hypotheses, it is possible that the observed results are affected by hypothesis confirming behaviour (Nichols and Maner, 2008) or suggestible participants subconsciously changing their experience to be compatible with the perceived demands (Dienes and Lush, 2023; Lush et al., 2020). As a countermeasure, comparing synchronous and asynchronous induction conditions of the RHI seems to be effective in controlling for suggestibility effects (Ehrsson et al., 2022). Even though embodiment and presence research could both be subject to this confound (Draper et al., 1998; Lush, 2020), this topic is only actively discussed in embodiment research (Ehrsson et al., 2022; Lush and Seth, 2022). Together, this calls for carefully planned designs for learning about the self and its interaction with the environment.

1.3 Self-environment interactions

Interacting with objects in our environment requires fine-tuned body movements toward the target object. For example, reaching for a cup of tea requires that we do not only know the relative position of our limbs, but also the position of our self and the target object in space. The target object can be encoded relative to the self, i.e., in an egocentric reference frame, or relative to other objects or landmarks, i.e., in an allocentric reference frame (Fiehler and Karimpur, 2023).

Egocentric reference frames are primarily found to be gaze-centred (Crawford et al., 2011; Medendorp et al., 2008). Consequently, gaze shifts and even whole-body translations produce pointing errors in line with a gaze-centred reference frame (Henriques et al., 1998; van Pelt and Medendorp, 2007). Such movements change the spatial relation between the self and the target object in an egocentric reference frame, requiring spatial updating of the target representation (Crawford et al., 2011). This might be more demanding when many objects have to be updated with the self's movements (Burgess, 2006).

Allocentric reference frames are independent of the self and a change in the self's spatial position does not affect the position of the target object relative to other objects or landmarks (Fiehler and Karimpur, 2023). Therefore, encoding a target object relative to landmarks is particularly relevant in memory-dependent tasks (Chen et al., 2011), such as reaching toward an alarm clock after switching off the light. Unnoticeably shifting landmarks introduces pointing errors in the direction of the shift (e.g., Byrne and Crawford, 2010; Karimpur et al., 2019), varying with the number of shifted landmarks (Fiehler et al., 2014; Klinghammer et al., 2015). Nevertheless, participants do not rely entirely on allocentric cues (e.g., Fiehler et al., 2014; Lu and Fiehler, 2020), suggesting that egocentric reference frames are also used when landmarks are available (Schütz et al., 2013). This poses the question of how egocentric and allocentric reference frames interact. In other words, here, one might ask whether allocentric reference frames are truly independent of the self.

Humans typically rely on both spatial reference frames to represent action targets (Chen and Crawford, 2020). This makes it necessary to combine egocentric and allocentric cues, e.g., by weighting both cues depending on their reliability (Byrne and Crawford, 2010) or by integrating them according to a Bayesian model (Camors et al., 2015). This suggests that the relative influence of egocentric and allocentric reference frames depends on the available cues. For example, if visual feedback for reaching movements is present, participants rely more on an egocentric reference frame. However, if the visual feedback is abolished, their reaching endpoints seem to be more strongly influenced by allocentric cues (Neely et al., 2008). This clearly shows that both spatial reference frames are used to guide goal-directed actions.

The central role of the self when interacting with objects in the environment is visible when considering how allocentric reference frames inform goal-directed actions. To guide actions toward a target object, it is necessary to convert allocentric representations into egocentric coordinates (Chen and Crawford, 2020). Studies have shown that this conversion happens relatively early. Using a task enabling participants to convert allocentric representations into egocentric coordinates after a first or a second landmark presentation showed that participants convert allocentric representations as soon as the information of the target location is available, i.e., after the first landmark presentation (Chen et al., 2011, 2018). This shows that egocentric and allocentric reference frames closely interact and highlights the role of egocentric processes in guiding movements in self-environment interactions.

1.4 Rationale of the studies

In summary, there is a complex interplay between the processes constituting the feeling of being a self in an environment and the self's interactions in this environment. Distinguishing what belongs to the self and thereby, separating the self from the environment, provides a basis for the subjective experiences of the self and, at the same time, enables the self to interact with its environment. The close interplay between egocentric and allocentric reference frames, as well as the reliance on egocentric coordinates for goal-directed actions, both indicate a central role of the self. To better understand the self in its environment, I conducted three studies to uncover key aspects of self-environment relations and interactions.

My first study investigated self-environment relations by reviewing embodiment and presence research. Although most of the studies investigated embodiment and presence in isolation, the literature suggests a relation between both processes (Nostadt et al., 2020). To further specify this relation, I developed the Implied Body Framework. In addition, my first study identifies important challenges for future research posed by demand characteristics (Lush, 2020; Orne, 1962). Presenting participants with questionnaire items might provide insights into the research hypotheses (Reader, 2022). I further investigated this confound in my second study by comparing participants' expected embodiment ratings in an online experiment to participants' actual ratings in a VR experiment (cf., Orne, 1962). Similarities between the two experiments would suggest that participants gained knowledge about the research hypotheses. Together, the first two studies investigated self-environment relations in VR by examining the relation between embodiment and presence processes, as well as challenges, inherent to testing participants' subjective experiences.

My third study focused on self-environment interactions by investigating participants' behaviour in VR. Interacting in an environment is intimately connected to the self and its position in space. This is also evident in the way self-independent allocentric representations become integrated into egocentric coordinates to guide actions (Chen and Crawford, 2020). It, thus, suggests that changes to the self's egocentric position might influence allocentric spatial coding, which I investigated in my third study.

2 Study I: Why we should rethink our approach to embodiment and presence

Forster, Karimpur, & Fiehler, 2022, *Frontiers in Virtual Reality*

In my first study, I reviewed embodiment and presence research and, based on the observed commonalities between the two processes, proposed a conceptual framework to unify embodiment and presence. In the following, I will summarise key points from my review and introduce the Implied Body Framework (IBF).

Previous studies mostly investigated embodiment and presence in isolation. Nevertheless, some similarities between both processes exist (Nostadt et al., 2020). For example, the term self-presence has conceptual commonalities with embodiment in that it describes a state in which participants experience a virtual body as belonging to themselves (Lee, 2004). That embodiment and presence are complementary concepts is also visible in the observation that interactions in the environment are important for both processes. While the agency component of embodiment refers to the feeling of control over one's own actions (Kilteni et al., 2012), presence was assumed to emerge when the environment responds appropriately to one's actions (Zahorik and Jenison, 1998). The relation between both processes is further supported by correlations between ownership and presence ratings (Roth and Latoschik, 2020). Most importantly, while embodiment contributes to what is perceived as belonging to the self, therefore making the body a pivotal point of embodiment, the body seems to contribute to presence as well (Pan and Steed, 2019; Slater, Spanlang, and Corominas, 2010). The IBF specifies this relation between embodiment and presence in a common framework.

In the IBF, implied bodies become integrated into a body representation on which presence depends (Figure 1). Multisensory correlations imply the existence of a body, i.e., an *implied body*. For example, head movements lead to an updated visual scene implying a body at the person's viewpoint (Figure 1, Implied Body 1). In the IBF, multisensory integration is a key component, which integrates plausible implied bodies into the body representation, i.e., they become embodied. Constituting a body representation provides

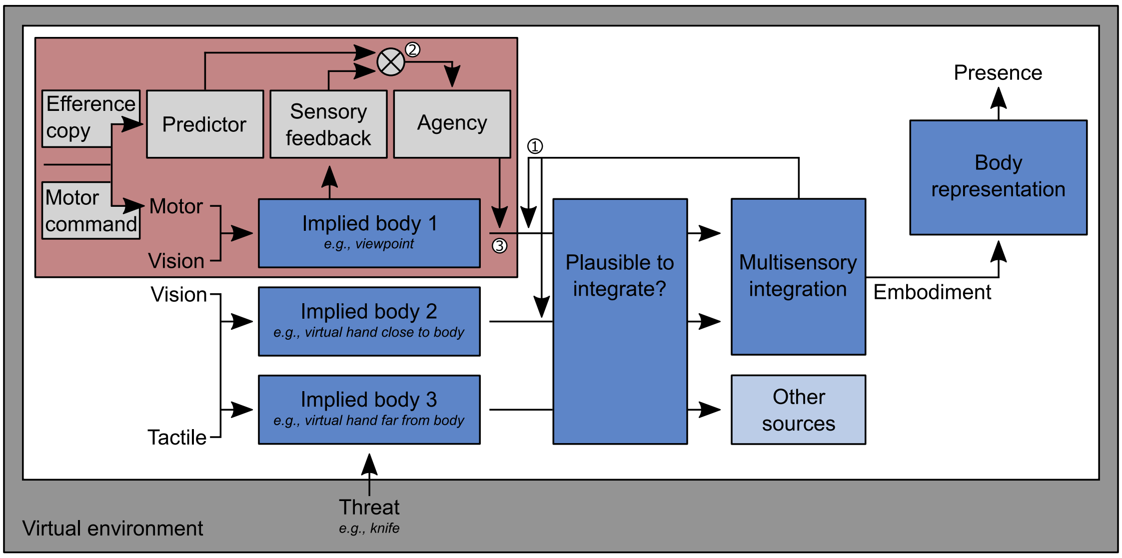

Figure 1. The Implied Body Framework (IBF). Multisensory correlations insinuate the existence of an implied body. If it is plausible that an implied body belongs to the body representation, it becomes integrated. Presence emerges in relation to the reference point of this body representation. (1) Feedback from multisensory integration can affect the weight of individual implied bodies, making them more or less likely to be integrated. (2) Comparing sensory feedback provided by implied bodies to predicted sensory consequences leads to agency, which can then (3) also influence the weighting of the implied bodies. Revised figure based on Forster et al., 2022b, p. 6.

a reference point indicating where the self is located in space, thereby giving rise to presence as the feeling of 'being there'. The IBF therefore suggests that presence depends on embodiment processes.

Integrating implied bodies into the body representation is an iterative process. The (1) feedback loop from multisensory integration influences the integration of implied bodies (Figure 1, feedback arrow). This happens by weighting the implied bodies, making it more or less likely that they appear plausible and become integrated. This makes the weights applied to implied bodies an important leverage point contributing to what becomes integrated into the body representation, and also allows self-environment interactions to influence the integration of implied bodies.

Agency (Figure 1, red box) emerges from (2) comparing sensory feedback, provided by implied bodies, to predicted sensory consequences in a comparator model (cf., Haggard, 2017). Actions are experienced as caused by the self if no prediction error between the sensory feedback and the predicted sensory consequences occurred. Importantly, experiencing agency over an implied body (3) makes it more likely that it belongs to the body representation.

The IBF specifies the relation between embodiment and presence processes. However, reviewing the literature also showed that demand characteristics are an important confound for embodiment and presence research (Lush, 2020; Orne, 1962). Showing participants the methods of a standard RHI experiment and letting them rate their expected feelings without actively participating in the experiment led to similar responses as in standard RHI experiments (Lush, 2020). This suggests that subjective ratings on embodiment and presence could be confounded by demand characteristics and shows important future research directions.

3 Study II: Demand characteristics challenge effects in embodiment and presence

Forster, Karimpur, & Fiehler, 2022, *Scientific Reports*

In my second study, I investigated demand characteristics as a possible confound in embodiment and presence research. To investigate this confound, I created an online and a VR experiment and compared the rating results from both experiments (cf., Orne, 1962).

In the VR experiment, participants stood in the centre of a virtual reconstruction of the VR laboratory and saw soap-bubbles float toward them, which they had to kick with their feet. The purpose of this task was to facilitate embodiment and presence processes by allowing participants to experience their fully motion-tracked virtual avatar by interacting with the virtual environment. We introduced a delay of 30 frames (~333 ms) to participants' virtual movements (synchronous and asynchronous) and manipulated the visibility of the avatar (visible and invisible). No combination of asynchronous movements and an invisible avatar was included. After each condition, participants rated questionnaire items on embodiment (ownership, location, and agency) and presence on a seven-point Likert scale.

In the online experiment, participants saw short video clips, illustrating the VR experiment. They rated the same questionnaire items as participants in the VR experiment after each condition. However, they were instructed to rate those items based on what they expected to experience, if they had participated in the experiment just presented to them.

In both the online and the VR experiment, viewing synchronous avatar movements and having a visible avatar body generally led to higher ratings of embodiment and presence (Figure 2). Similar results in the online and VR experiment show that demand characteristics confound questionnaire ratings on embodiment and presence. Thus, participants' ratings in the VR experiment might be based on expectations formed by performing the experiment.

Furthermore, demand characteristics might have a particularly strong influence on highly suggestible participants. In an additional analysis, I tested the influence of suggestibility, measured by the sensory suggestibility scale (Lund et al., 2015), on participants' rating responses. The sensory suggestibility scale consists of small exercises suggesting an illusory perception. In these exercises, participants rate for example how strongly they saw a bluish colour after applying a soft pressure onto their closed eyes. The results show that participants in the asynchronous movement condition rated ownership and location questionnaire items as higher if they scored high on suggestibility. This suggests that suggestibility might confound synchronous and asynchronous conditions differently.

Together, this study highlights that participants in embodiment and presence experiments might form expectations matching the research hypotheses. Demand characteristics could consequently bias participants' responses when relying on subjective embodiment and presence ratings.

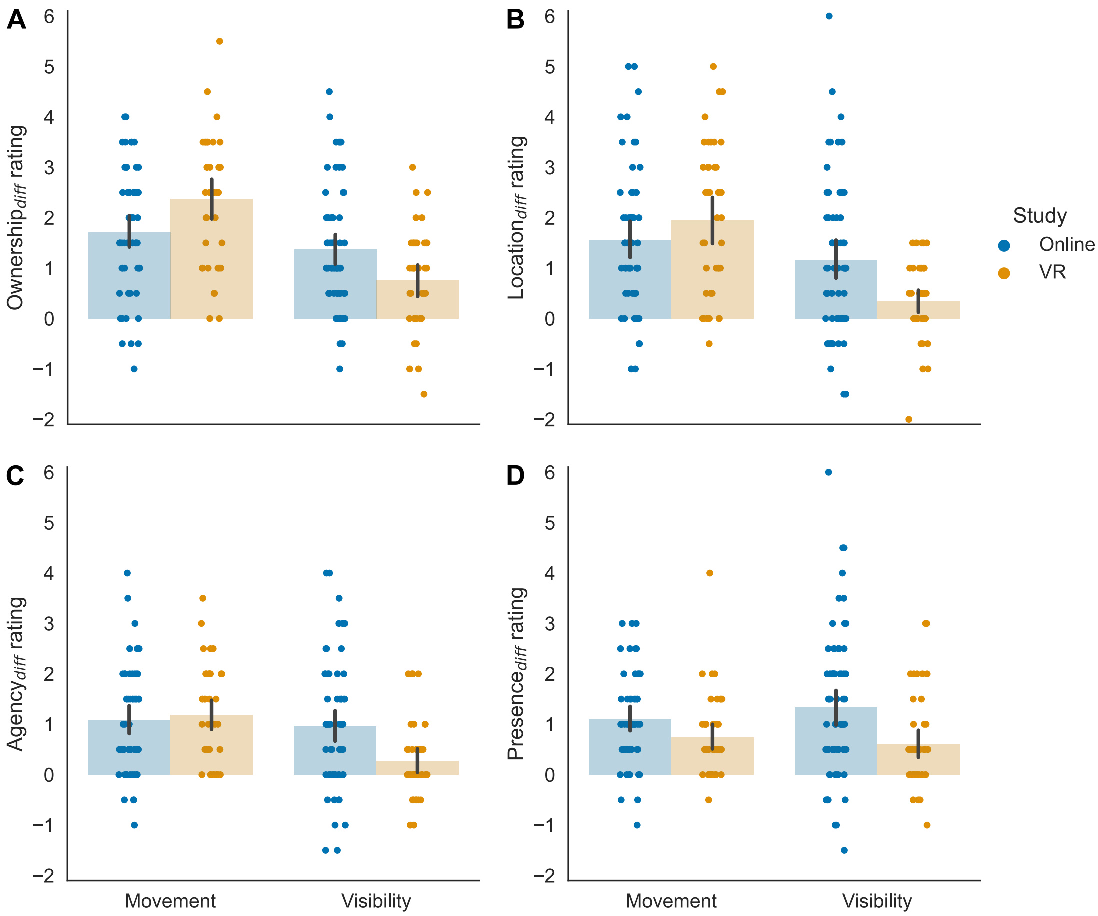

Figure 2. Difference in rating responses for **(A)** ownership, **(B)** location, **(C)** agency and **(D)** presence ratings, depending on movement and visibility manipulations. Rating differences are positive if participants rated conditions with synchronous movements or a visible avatar body higher than asynchronous movements or invisible avatar conditions, respectively. Error bars show the 95 % within-subject confidence intervals. Revised figure based on Forster et al., 2022a, p. 9.

4 Study III: Egocentric cues influence the allocentric spatial memory of object configurations for memory-guided actions

Forster, Fiehler, & Karimpur, 2023, *Journal of Neurophysiology*

In my third study, I examined self-environment interactions by investigating the use of different spatial reference frames when interacting with objects in an environment.

I was particularly interested in testing if egocentric cues influence allocentric spatial coding.

The influence of allocentric reference frames was frequently tested by letting participants reach toward a target object, while landmarks are slightly shifted during a memory delay (e.g., Byrne and Crawford, 2010; Lu and Fiehler, 2020). Extending this object-shift paradigm to include an observer shift in addition to a landmark shift allowed to test the contribution of both egocentric and allocentric cues, respectively.

In a VR experiment, participants were instructed to reproduce a configuration of six balls memorised from an encoding scene (Figure 3). The landmark shift was realised by briefly presenting some of the balls (one, three, or five) from the encoding scene at a slightly shifted location after a memory delay. To simulate a shift in the observer's position, the camera position in VR was moved laterally.

I used egocentric and allocentric weights to test how much participants relied on the respective egocentric and allocentric cues. These weights were calculated by comparing participants' baseline-corrected ball placement errors against the maximally expected placement error, i.e., the amount of landmark or observer shift. An egocentric weight of for example 0.5 suggests that participants relied to 50 % on egocentric cues.

There might also be influences on participants' ball placements within a given configuration of balls. Calculating the configurational error quantifies those influences. This

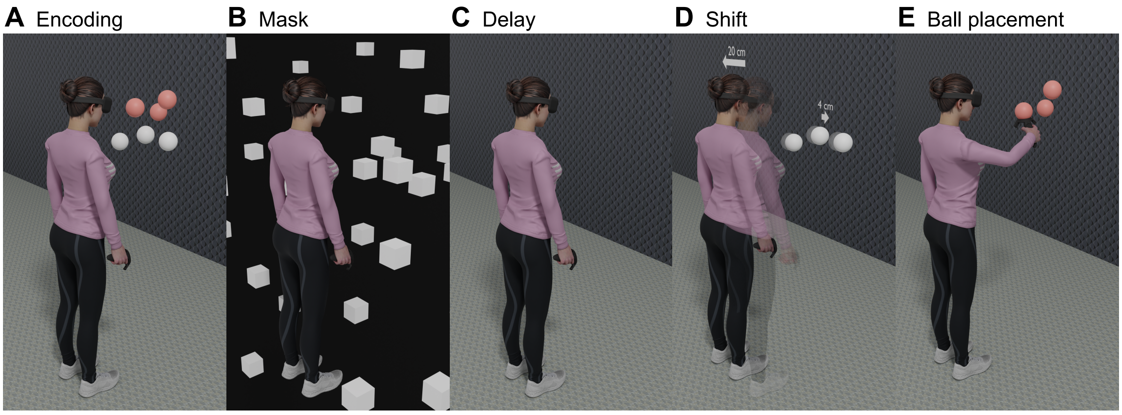

Figure 3. Depiction of the trial sequence. **(A)** The participant sees the encoding scene containing a configuration of six white balls in VR (5,000 ms). Balls are colour coded for visualisation purposes. White balls will later reappear as landmarks, coral balls will later be target objects. After **(B)** a mask (200 ms) and **(C)** a small delay (1,800 ms), **(D)** landmark and observer positions could be shifted. For the landmark shift, one, three or five landmarks reappeared in the test scene at a slightly shifted location, unbeknown to the participant (1,000 ms). For the observer shift, the camera position in VR was moved laterally (1,000 ms). The participant then **(E)** reproduces the configuration of balls remembered from the encoding scene. Revised figure based on Forster, Fiehler, and Karimpur, 2023, p. 20.

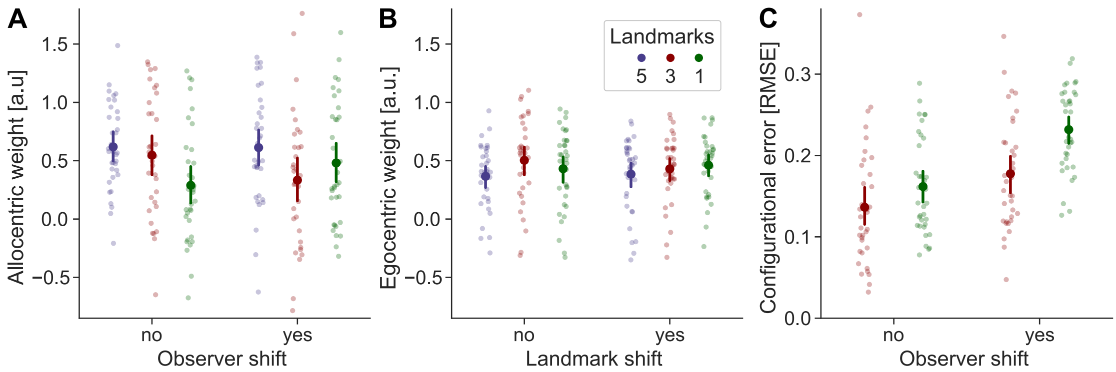

Figure 4. Results for **(A)** the allocentric weight, **(B)** the egocentric weight and **(C)** the configurational error. Although the landmark shift did not affect the egocentric weight, it was included in this figure to make the comparison to the allocentric weight easier. Error bars show the 95 % within-subject confidence intervals. Revised figure based on Forster, Fiehler, and Karimpur, 2023, p. 23.

measure is based on a Procrustes analysis (Gower, 1975; Krzanowski, 2000) and describes how well the ball configuration reproduced by participants matches the one presented in the encoding scene. Values of 0 indicate that both configurations perfectly match, while increasing deviations from the initially presented configuration are represented by higher values.

Egocentric weights increased and allocentric weights decreased with fewer presented landmarks (Figure 4). This shows that the relative influence of egocentric and allocentric cues depends on the reliability of allocentric landmark information. Furthermore, the configurational error increased when fewer landmarks were presented or the observer was shifted. This shows that egocentric cues impact the allocentric memory of object configurations. Together, these findings highlight the narrow interplay between egocentric and allocentric reference frames and show the importance of self-related processes in interacting with objects in the environment.

5 Discussion

5.1 Summary

In this thesis, I investigated different aspects of self-environment relations and interactions. My first study specified the close connection between embodiment and presence, supported by actions, in a conceptual framework, the IBF. It provides a holistic view to help with better understanding self-environment relations and their interactions by combining research from different fields. However, reviewing the literature also pointed toward future research challenges. My second study directly compared an online and a VR experiment and showed that demand characteristics are an important confound in embodiment and presence research. This shows that it is important to consider this challenge when testing subjective experiences of the self in future experiments. My third study tested self-environment interactions by letting participants reproduce a configuration of balls in VR. The results showed that the egocentric perspective of the self influences allocentric spatial coding. This highlights the role of self-related processes for goal-directed actions in an environment. Together, the three studies show the close interplay between self-related processes when interacting with the environment, as well as the challenges associated with investigating the self.

5.2 Processes evoking the feeling of being a self in an environment

My first study investigated the relation between embodiment and presence and proposed the IBF as a common framework for both processes. Previous work suggested guiding principles that unify embodiment and presence as a way to facilitate teleoperation designs (Nostadt et al., 2020). At the first level of these principles, technical properties of the device and agency are most important. At the second level, moving through an environment is supported by the location of the self relative to the body and the environment. Finally, at the third level, virtual body parts become integrated into the body representation resulting in ownership. The exact relation of embodiment and presence remained unspecified in these guiding principles, which is an important contribution of the IBF.

The IBF proposes that embodiment provides a basis for presence. Feeling present in the absence of a virtual body representation (cf., Gromer et al., 2019) could therefore be based on a basic form of embodiment (cf., Nostadt et al., 2020). In the IBF, head movements leading to an updated visual scene might be sufficient to imply the presence of a body, even though no virtual avatar body is visible. This fits well with the finding that visuotactile correlations in the absence of a virtual body representation facilitate the feeling of owning an invisible body (Guterstam et al., 2015) and shows that future research needs to investigate both processes jointly.

Furthermore, the IBF proposes that actions in an environment closely interact with embodiment processes, reflected by the inclusion of the comparator model into the IBF (cf., Haggard, 2017). This close interplay between actions and embodiment in the IBF is reflected in the observation that agency can influence embodiment (Abdulkarim et al., 2023; Tsakiris et al., 2006), while both processes remain independent (Abdulkarim et al., 2023; Kalckert and Ehrsson, 2012). Moreover, repeated interactions with the environment might change the weighting of the implied bodies in the IBF, suggesting that embodiment and presence could change over time.

A previous study suggested that ownership ratings are stable over time in a static version of the RHI (Bekrater-Bodmann et al., 2012). However, this study did not use a design which allowed for active self-environment interactions. I followed up on this question in an ongoing study (Forster, Karimpur, et al., 2023). In a version of the VR task from my second study, participants kicked virtual soap bubbles over eight sessions. Preliminary results suggest that participants' ownership and location ratings increase over time, but only in the asynchronous movement condition. There are two possible explanations for this finding. First, participants might adapt to the movement delay leading to higher ratings in the asynchronous condition (van Dam and Stephens, 2018). Second, suggestibility increases participants' ownership and location ratings specifically in the asynchronous condition, as suggested by my second study. I plan to follow up on this in coming experiments.

5.3 Demand characteristics confound subjective measures of the self

In my second study, I investigated challenges in embodiment and presence research and showed that participants can gain insights into the research hypotheses. This finding supports studies investigating demand characteristics in embodiment research (Lush, 2020; Reader, 2022) and shows that previously untested concerns about this confound in presence research are justified (Draper et al., 1998). It is therefore important to figure out how exactly demand characteristics affect participants' responses. Results might differ depending on whether or not participants' expectations are in line with the research hypotheses and whether they are motivated to confirm or reject those hypotheses (Corneille and Lush, 2023).

To test more directly if perceived demands translate into biased responses, one could manipulate participants' expectations and test if this affects their responses (Corneille and Béna, 2023). For example, one could explain to participants that the asynchronous stroking condition in the RHI leads to the feeling of ownership. An attempt to manipulate participants' expectations in this way remained unsuccessful, showing no effect of the instructions on participants' expectations (Lush et al., 2020). Even though participants' expectations remained unaffected by varying the instruction in this particular experiment, questionnaires might nonetheless provide demand characteristics capable of biasing their responses (Reader, 2022).

Moreover, participants are not necessarily aware that their responses are biased. In my second study, suggestible participants gave higher ratings in the asynchronous movement condition. Similarly, other studies suggest that suggestibility influences participants' rating responses in the synchronous (Lush et al., 2020; Marotta et al., 2016) and asynchronous conditions (Lush et al., 2020). This shows that suggestibility should be taken into consideration when designing experiments on embodiment and presence. However, this does not rule out that multisensory integration is also an important factor that contributes to results in embodiment research (Slater and Ehrsson, 2022). Together, to reduce bias when investigating the self in its environment, one could design experiments that go against participants' expectations or where they know little about the experimental purpose or measures.

5.4 Self-related processes that guide goal-directed actions

My third study tested self-environment interactions and showed that egocentric processes impact participants' allocentric spatial memory. This could be explained by findings that humans convert allocentric representations into egocentric coordinates for goal-directed actions (Chen and Crawford, 2020; Chen et al., 2011, 2018). In line with this, another study showed that walking to a new position before placing target objects at the remembered positions increased placement errors. Importantly, these errors increased the more objects had to be remembered, showing that spatial updating of the egocentric target positions, rather than remembering target objects allocentrically, explained the results (Wang et al., 2006). Together, this could suggests that spatial updating of the self's egocentric position affects allocentric memory when combining egocentric and allocentric representations for goal-directed actions.

Furthermore, the available landmarks contribute to the integration of egocentric and allocentric cues (Byrne and Crawford, 2010), especially if they are task relevant (Klinghammer et al., 2015). My third study suggests that participants rely more strongly on allocentric reference frames when more landmarks are available (cf., Fiehler et al., 2014; Klinghammer et al., 2015), and otherwise fall back to use egocentric reference frames. In line with this, reaching toward a target, while the spatial stability of the landmarks is manipulated, showed that the stability of the landmarks impacts how participants integrate egocentric and allocentric cues (Byrne and Crawford, 2010).

Another important factor that influences the contribution of allocentric and egocentric cues is whether interactions are memory-guided or controlled online. Studies showed that allocentric reference frames are most relevant for memory-guided tasks (Chen et al., 2011; Lu and Fiehler, 2020). My third study shows that egocentric cues nevertheless influence allocentric spatial coding in memory-dependent tasks. This contribution might further change in favour of egocentric reference frames when the target object is visible during the reaching movement. Intersecting a dot on a tilted screen by moving one's finger over a tablet lying flat on a table showed that participants predominantly relied on egocentric reference frames. This was the case, even though they would benefit from using allocentric cues because of a spatial bias applied to the position of the cursor, background, and target (Crowe et al., 2021), showing that participants highly rely on the egocentric position of the self. Moreover, results from this study might also indicate a prominent role of egocentric reference frames when extending the self's actions to a remote space, opening opportunities for practical applications in teleoperation.

5.5 Human factors in teleoperation

We are used to interacting in the space immediately surrounding us; however, many environments are dangerous (e.g., due to contamination) or difficult to access (e.g., another planet). Teleoperation systems allow human operators to safely extend actions from their immediate surroundings to remote environments (Figure 5). In these systems, human actions at a local site are registered by a computer and translated into actions of a robot at a remote site. Feedback of the action is then sent back to the human operator (Moniruzzaman et al., 2022). Tilting a joystick to the left can then for example result in an unmanned vehicle steering to the left and the human operator receiving visual feedback of the left turn. This is a delicate task requiring an excellent fit between human and machine which makes it necessary to consider the human operator in the design of teleoperation systems (Adamides et al., 2015). Self-related processes and their contribution to goal-directed actions can therefore inform teleoperation designs.

Self-related processes to interact in remote spaces

Presence or telepresence is especially relevant to teleoperation because of the potential link to task performance (Cooper et al., 2018; Peer et al., 2010). The IBF suggests that embodiment provides a foundation for presence. Enhancing the user's embodiment in

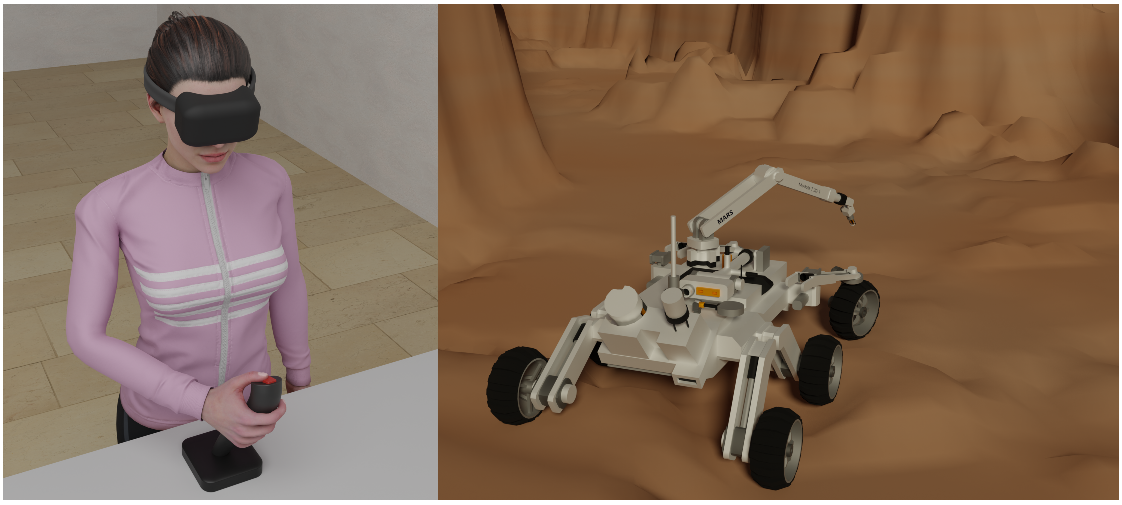

Figure 5. A teleoperator operating a rover on the Mars. Using VR as a tool in future teleoperation systems provides the opportunity to virtually transport the self to a remote site, where the user feels embodied and present. It therefore has the potential to change the role of the operator from operating a machine to being the actor at a remote site. The avatar model was taken from www.mixamo.com.

a teleoperation system should therefore increase presence. It, thus, makes embodiment directly relevant for teleoperation designs.

Designing robotic arm movements that resemble human movements has improved task performance when learning to control a new teleoperation system (Mick et al., 2022; Zhou et al., 2023). However, this advantage over non-matching arm movements disappears after participants become more experienced with the teleoperation system (Mick et al., 2022). Furthermore, using non-matching control schemes, e.g., holding two fingers up to make a power grip with a bionic hand, seems to be advantageous when transferring skills to a new control scheme (Schone et al., 2023). Learning to control a new teleoperation device or repeated switching between different systems will therefore likely benefit from different control strategies, challenging teleoperation designers to create teleoperation systems for specific use cases.

Designing teleoperation systems also poses the question of how much embodiment and presence is desired in a given teleoperation scenario. The finding that participants physiologically react to threat against an embodied tool roughly resembling a human hand (Cardinali et al., 2021), suggests that human operators could show similar reactions when the teleoperated machine becomes endangered. The feeling of ownership might therefore negatively affect task performance by increasing the user's risk perception (Shin et al., 2021). This makes it important to consider this relationship in the design of teleoperation systems. Based on the IBF and the finding that ownership and agency are separate processes (Kalckert and Ehrsson, 2012), it seems possible to design teleoperation systems that provoke low feelings of ownership, while simultaneously preserving agency over the operated tool. However, this might have other limitations, such as the user responding inappropriately to dangerous situations.

Challenges in teleoperation

Aside from technological challenges like overcoming communication delays between the local and the remote site, the fit between the human operator and the teleoperation system also needs to be considered (Moniruzzaman et al., 2022). Task performance is probably the most important criterion when it comes to evaluating a particular teleoperation design (Chan et al., 2014).

A connection between presence and task performance makes intuitive sense because immersing a user in a remote environment that feels similar to the real world should lead to comparable performance (Nash et al., 2000). However, if embodiment and presence are evaluated by subjective rating scales, it can be questioned whether a positive relation between these two processes and performance (Cooper et al., 2018; Grechuta et al., 2017; Peer et al., 2010), reflects a genuine connection between the two or if it is merely driven by demand characteristics.

To make full use of embodiment and presence in future teleoperation designs, it is necessary to clarify their relation to task performance (Welch, 1999). This ensures that teleoperation designs are focused on the most important factors influencing the user's interactions in a remote environment. One such factor might be concerned with the interaction between different spatial reference frames.

Acting in remote spaces

Spatial reference frames are highly relevant to perform teleoperation tasks, such as steering an unmanned vehicle to take samples of rock with a gripper arm. Despite this, only few studies have investigated how human operators use spatial reference frames in teleoperation.

Landmarks in a remote environment share the same space as the teleoperated machine. This might make them beneficial for guiding movements of a machine at a remote site, which the operator only sees on a computer screen. This is supported by the finding that participants use landmark information to reach toward a target object in a computer mediated environment. In addition, if the landmark is a familiar object, it further reduces reaching errors (Ferrel et al., 2001). This suggests that landmarks, particularly if the operator is familiar with them, can help to more accurately judge the target position in the remote environment. However, egocentric reference frames might also contribute to teleoperated interactions.

To provide a better overview over the remote environment, a control centre for teleoperation tasks might present a human operator with multiple views simultaneously (cf., Chew et al., 2021; Hainsworth, 2001). However, based on the results of my third study, a drawback of such set-ups might be that shifting one's gaze to a different view, while performing a teleoperation task, could negatively affect the memory of the target position relative to the landmarks and might therefore increase errors. In addition, multiple views of a remote environment might introduce a misalignment between the reference frame of the input device and the camera view. Correcting for this misalignment seems to be beneficial (Wu et al., 2023). Spatial reference frames are, thus, not only important for interacting in the space surrounding the self, but also to aid remote interactions. In sum, teleoperations provide a promising application, for which self-environment relations and interactions, as well as challenges related to demand characteristics, play an important role.

5.6 Conclusion

This thesis highlights the role of the self and its relation to the environment in the face of actions. Self-related processes determine what belongs to the self and therefore, contribute to how the self experiences its environment. Specifically, I showed that embodiment and presence processes are closely connected. Investing these subjective experiences of the self is a challenging task that can provide further insight into how the experiences of the self shape interactions with its surrounding environment. The self might thus be fundamental to the support of goal-directed actions in the world, while being concurrently shaped by its actions. The fundamental role of self-related processes is also evident in the way they influence other seemingly independent processes. In particular, this can be seen in the way egocentric cues impact allocentric spatial memory, showing that the self's spatial position in the environment is central to successful self-environment interactions. The close interplay between self-related processes and their contribution to self-environment interactions make them inevitable tools for future technological developments. One potential field of application is extending the self's actions to teleoperated machines at a remote site.

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II Publications

1 Study I: Why we should rethink our approach to embodiment and presence

Forster, Karimpur, & Fiehler, 2022, *Frontiers in Virtual Reality*

frontiers | Frontiers in Virtual Reality

REVIEW
published: 04 July 2022
doi: 10.3389/frvir.2022.838369

Why we Should Rethink Our Approach to Embodiment and Presence

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When interacting with objects in the environment, it feels natural to have a body which moves in accordance to our intentions. Virtual reality (VR) provides a tool to present users with an alternative virtual body and environment. In VR, humans embody the presented virtual body and feel present in the virtual environment. Thus, embodiment and presence frequently co-occur and share some communalities. Nevertheless, both processes have been hardly considered together. Here, we review the current literature on embodiment and presence and present a new conceptual framework, the Implied Body Framework (IBF), which unifies both processes into one single construct. The IBF can be used to generate new hypotheses to further improve the theoretical conceptualisation of embodiment and presence and thus, facilitate its transfer into application.

Keywords: body ownership, rubber hand illusion, implied body framework, demand characteristics, virtual reality, presence

OPEN ACCESS

Edited by:
Doug A. Bowman, Virginia Tech, United States

Reviewed by:
Richard Skarbez, La Trobe University, Australia
Daniel Roth, University of Erlangen Nuremberg, Germany

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

Received: *17 December 2021*
Accepted: *19 April 2022*
Published: *04 July 2022*

Citation:
Forster P-P, Karimpur H and Fiehler K (2022) Why we Should Rethink Our Approach to Embodiment and Presence. Front. Virtual Real. 3:838369. doi: 10.3389/frvir.2022.838369

1 INTRODUCTION

The interaction between the self and the environment is fundamental to human lives. It provides our body with nourishment and helps us to react when confronted with potential dangers. Similar to real life, we feel a strong distinction between ourselves and the environment in virtual reality (VR), i.e., a feeling to be a separate entity within the environment. Whether we experience a virtual or the actual physical environment, processes of embodiment and presence are an essential element of this experience. This has direct and practical implications. First, in-depth knowledge of embodiment and presence can help us to improve VR experiences. For example, when playing VR games, body movements can be tracked and mapped onto an avatar. Neural networks can be used to predict these movements, which can then be fed back, mapping the future movement states on the avatar. This lead to a stronger believe that the players were in the virtual environment, with the avatar at the same location as their real body (Schwind et al., 2020). Second, patients might benefit from advances in embodiment and presence research, e.g., when conducting mirror therapy to alleviate phantom limb pain (Ramachandran and Rogers-Ramachandran, 1996; Wang et al., 2021, but see also; Barbin et al., 2016), or using exposure therapies to treat phobias (c.f., Ling et al., 2014). Knowledge from embodiment and presence research can therefore improve practical applications in VR and real life. However, transferring knowledge is currently hindered by the lack of an agreed upon common framework accounting for a possible relation between both processes (**Section 1.2**), and methodology problems (**Section 1.3**). Here, we review the relevant literature including previous frameworks (**Section 1.4**), and propose a new conceptual framework accounting for the possible relation of embodiment and presence (**Section 2**).

1.1 Conceptualisations of Embodiment and Presence

In this review, we describe embodiment as the process which integrates bodily entities, like a rubber arm (de Vignemont, 2011), into the body representation. The experiential properties arising from

FIGURE 1 | Setup of the rubber hand illusion. The rubber hand model was taken from www.turbosquid.com under their standard license, and the avatar model from mixamo.com.

this integration process structure embodiment by describing sensations relating to our body, i.e., *ownership*, *location*, and *agency* (Kilteni et al., 2012a, see also; Longo et al., 2008). Hereby, ownership describes the feeling that the body belongs to us; location refers to a sense of where we locate self and body relative to each other; and agency is the feeling of being in control of one's own actions.

Various conceptualisations have been proposed for presence. *Telepresence*, for example, was used to describe the user's virtual transportation to another place, where a machine on the real site is controlled by the user (Sheridan, 1992; Minsky, 2010). Performing bodily actions and receiving appropriate sensory feedback were considered as important characteristics of telepresence (Minsky, 2010). For VR applications, it is important that a definition of presence also encompasses presence in virtual environments, where a real counterpart does not necessarily exist. Following an influential review (Lee, 2004), presence can be divided into *physical-* (experiencing a virtual environment as real and unmediated), *self-* (experiencing a virtual body as one's own body), and *social-presence* (experiencing virtual others as real). The term *co-presence* is related to this latter component, but focusses on "being together" with others (Slater et al., 2000). The definition of physical presence does not require that the participant has the feeling to "be there" (c.f., Lee, 2004), which is another commonly used description of presence (e.g., Schubert et al., 2001; Slater et al., 2009). This sense to "be there" and the feeling that events in VR are real, are also covered by the terms *place illusion* and *plausibility illusion* (Slater, 2009; Slater et al., 2010a). *Spatial presence* sets a similar focus, encompassing "being there" and experienced opportunities for actions (Wirth et al., 2007). Altogether, having a sense to be within an environment, which comprise the feeling to be located within the respective environment, is fundamental to generate a sense of presence. Acting in this environment might thereby directly link to perceiving the environment as real (c.f., Zahorik and Jenison, 1998).

Some of those definitions describe components indicating a conceptual overlap between embodiment and presence (c.f., Lee, 2004). In addition, to feel present in an environment, more precisely, to "be there," is enhanced by the body (c.f., Slater, 2009; Slater et al., 2010a), which might give a reference for where one feels present. As embodiment determines what we perceive as belonging to our body, presence might depend on the product of embodiment. This poses a fundamental question: How do embodiment and presence relate to each other? Investigating this question is especially important for clinical and industry applications that build on this knowledge.

1.2 Relation Between Embodiment and Presence

Relating embodiment and presence is not entirely new, but rather underrepresented in the current literature. A positive example can be found in a seminal paper from Kilteni et al. (2012a), which mentions that presence could be included in a broader definition of embodiment. A recent review (Nostadt et al., 2020) offers guiding principles to facilitate the construction of such a common framework. Following these principles, mechanical fidelity is on the lower level and describes how well participants can interact in a virtual environment. Spatial bodily awareness is placed at an intermediate level and helps when moving through this environment, as it relates to one's own location in the environment. The topmost level describes self-identification, which relates to ownership. Given this hierarchical structure, improvements in the location component and presence (both part of spatial bodily awareness) should directly contribute to the feeling of ownership. However, interactions between different levels are not yet defined. These guiding principles help to structure the concepts of embodiment and presence, but do not explain the underlying mechanisms that link the two.

Concerning the embodiment components, ownership is conceptionally similar to self-presence, which emerges when participants perceive a virtual body as their own, i.e., when ownership is perceived (c.f., Lee, 2004). The location component and the feeling to "be there" are also conceptionally similar, as they refer to where we locate ourselves. However, both address distinct spatial components, i.e., one's own location with respect to a body or within an environment (Kilteni et al., 2012a). The latter is especially important to perform actions and to engage with objects or other agents. Performing actions might support presence, in particular telepresence, where the participant is virtually transported to another environment to perform remote actions. For example, when operating a rover on the moon, we might feel present because of the agency we feel when tipping a joystick forward and experiencing immediate consequences on the image that is provided on the monitor. This links presence to actions and suggests that we feel present, when the virtual environment responds in the same way to our actions, as we expect it from the real environment (Zahorik and Jenison, 1998).

Given potential links between embodiment and presence, we would expect that both processes influence each other, but are still separate processes. Accordingly, positive correlations have been reported between questionnaire items on ownership and presence (Roth and Latoschik, 2020). That both processes are nevertheless distinct can be observed when changing the perspective (first-person-perspective or third-person-perspective) over a virtual body. Changing the perspective in a VR experiment showed that a first-person-perspective is important for the feeling of ownership and location, but lacked an effect on spatial presence (Gorisse et al., 2017). However, ownership over a body seen from a third-person-perspective is possible (Ehrsson, 2007), suggesting that manipulating perspective declines, but does not abolish embodiment.

Decoupling presence from the perspective over a body might enable participants to feel present even though a virtual body is not presented. This implies a strong separation between embodiment and presence. As participants can experience some form of embodiment even with an invisible body (Guterstam et al., 2015), it remains unclear whether both processes are truly separated in such situations. Considering the role of the body for the sense of presence can provide additional insights.

Previous work suggests that VR avatars capturing individual body characteristics, e.g., based on 3D body scans of the participant, can enhance the sense of presence and ownership (Waltemate et al., 2018). In general, a body itself is important for establishing a sense of presence (Slater, 2009; Slater et al., 2010a; Pan and Steed, 2019; but see also; Steed et al., 2016; Wolf et al., 2020). Steed et al. (2018) manipulated avatar visibility in VR and found that a visible avatar improved participants feeling to "be there" and to perceive the virtual environment as real. These feelings benefitted even more when other virtual avatars glanced at the participant, making it important for participants to have a virtual body, although it was not the main contribution to presence. Other studies used a setup which required participants to optimise their experience in VR to enhance presence. This required participants to add features like an increased field of view to their VR experience. The results indicate that having an avatar is important to feel present, or having a place illusion, in the virtual environment (Slater et al., 2010a, see also; Llobera et al., 2021). The avatar might serve as a spatial reference point and thereby promote presence. This suggests that embodiment and presence depend on similar information and that presence might build upon embodiment processes. Such a conceptual overlap between embodiment and presence likely translates into methodological difficulties in separating both processes.

1.3 Measures of Embodiment and Presence

There are several challenges concerning currently used measures of embodiment and presence (for a review on measures see Kilteni et al. (2012a), who include measures of embodiment; and Grassini and Laumann (2020) and Souza et al. (2021), who discuss measures of presence). It is unclear whether these challenges arise from their validity or discriminant power to separate between the two processes. A lack of validity requires to reconsider and improve these measures. If embodiment and presence are more closely related than previously thought, studies would likely fail to measure each process individually, but instead would need to consider their relations to finally extract their differential contributions to the underlying mechanism.

The validity of currently used subjective measures in embodiment and presence research is rather questionable. Questionnaire items measuring embodiment (e.g., Botvinick and Cohen, 1998; Longo et al., 2008) or presence (e.g., Witmer and Singer, 1998; Slater and Steed, 2000) are repeatedly used, but a standardised instrument is currently missing. Some studies aimed to create questionnaires by considering psychometric properties (e.g., Roth and Latoschik, 2020), but currently used measures are far from being comparable to diagnostic instruments (e.g., Raven's Standard Progressive Matrices, Raven, 2003). In addition, questionnaire items are open to participants' interpretations, when they are trying to make sense of the posed questions (Usoh et al., 2000). More extreme, one might ask whether the reported percept in questionnaires was experienced at all, or only constructed post-hoc after being questioned about it (Slater, 2004). This suggests that questionnaires alone are inappropriate to measure embodiment and presence.

However, combining questionnaires with objective measures might not be sufficient to overcome shortcomings, as the validity of objective measures can also be questioned. For example, in the rubber hand illusion (RHI, see **Box 1** and **Figure 1**), proprioceptive drift is frequently used to assess embodiment (e.g., Botvinick and Cohen, 1998; Kalckert and Ehrsson, 2014a), but might be inappropriate to discriminate between ownership and location (Longo et al., 2008; Kilteni et al., 2012a). Further, proprioceptive drift and ownership/RHI items might be dissociated (Holle et al., 2011; Abdulkarim and Ehrsson, 2016), which could explain why both measures are sometimes unrelated (Crucianelli et al., 2013; Walsh et al., 2015). A similar finding can be observed for attempts to validate physiological measures of embodiment (e.g., Ehrsson et al., 2008; Petkova and Ehrsson, 2008) or presence (Meehan et al., 2002) with questionnaires, where some studies report their physiological measures to be in accordance with sensations described in the administered questionnaire (Slater et al., 2010b; Yu et al., 2012; Preuss and Ehrsson, 2019), but others fail to find such a relationship (e.g., Peperkorn et al., 2015; Kokkinara et al., 2016; Eftekharifar et al., 2020). Validating objective measures is additionally challenged by findings showing that objective and subjective measures, for both, ownership and agency, do not entirely depend on the same underlying information (Ma et al., 2021; Qu et al., 2021).

This clearly shows that the quality of subjective and objective measures needs to be improved. Despite challenges related to validity, it is also likely that the measures in use cannot clearly discriminate between embodiment and presence. For

BOX 1 | The Rubber Hand Illusion.

What is the rubber hand illusion? Embodiment has attracted broad scientific interest after Botvinick and Cohen (1998) described the rubber hand illusion (RHI). In this setup (**Figure 1**), participants receive brush strokes on their own hidden hand that are synced to strokes on a rubber hand that is in full view, directly in front of them. It is argued that multisensory integration enables the illusion that the rubber hand belongs to one's own body. Under this view, visual and tactile sensations are integrated, and proprioceptive information becomes subsequently adjusted to match the congruent information of the other two modalities (Botvinick and Cohen, 1998).

Which control measures are used? Botvinick and Cohen (1998) introduced two control measures to capture suggestibility effects. First, they used stroking synchrony to manipulate multisensory integration. The RHI occurred after synchronous but not asynchronous stroking. Second, they used a set of experimental and control questionnaire items (but see, Lush, 2020). An illusory effect was reflected in higher ratings of the experimental questions. These manipulations and control items have been widely used in embodiment research.

Are there objective measures? During the RHI, the sensed position of the real hand becomes biased towards the rubber hand, to match congruent information from vision and touch (Botvinick and Cohen, 1998). *Proprioceptive drift* is one of the widely used objective measure to assess this bias (e.g., Botvinick and Cohen, 1998; Kalckert and Ehrsson, 2012; Ma et al., 2021). Participants have to indicate the perceived position of their unseen hand, with the hand not used during the RHI by relying on proprioception (Botvinick and Cohen, 1998). If the perceived position drifts towards the rubber hand, it is generally interpreted as an indication of having embodied the fake hand (but see, Rohde et al., 2011; Fuchs et al., 2016).

What about modern approaches? Since the introduction of the RHI, embodiment was investigated in various setups (e.g., Kalckert and Ehrsson, 2012; Chancel and Ehrsson, 2020). Some allowed finger movements of the rubber hand (e.g., Kalckert and Ehrsson, 2012), which adds the possibility to test for agency. Currently, more studies on embodiment are run in VR (e.g., Kilteni et al., 2012b; O'Kane and Ehrsson, 2021), thereby providing more flexibility and the opportunity to test conditions where the position of the virtual and the real arm overlap (c.f., Ma et al., 2021), which was impossible with the original RHI setup.

questionnaire measures, this is evident in positive correlations between ownership and presence (Roth and Latoschik, 2020). Further, it is unclear if physiological measures can distinguish both processes. For example, in a height exposure task in VR, the observed response in objective measures could be attributed to three possible causes: the participant having embodied an avatar, the participant feeling present in the virtual environment, or both. This is evident in experiments using the same measures in similar setups and interpreting them as indicator for one or the other process (c.f., Meehan et al., 2002; Galvan Debarba et al., 2017), hindering the differentiation between embodiment and presence based on physiological measures.

At the current stage it is unclear whether measures of embodiment and presence are challenged by a lack of validity, discriminability, or both. One possible solution is to measure participants experiences in VR, without explicitly referring to the underlying constructs. This can be realised by letting them manipulate their own and/or the virtual environment's appearance, e.g., if they would like to have an avatar representing their body. This can thereby indicate which factors improve participants' VR experience (c.f., Murcia-López et al., 2020; Llobera et al., 2021). Although this is an encouraging approach to solve these challenges, it might be less applicable when trying to understand the underlying constructs. In this case, the development of adequate measures requires knowledge on how embodiment and presence are related, which can be facilitated by the development of a common framework. Such a framework should also account for already existing conceptualisations of both processes.

1.4 Previous Work on Embodiment and Presence Frameworks

When introducing the RHI, Botvinick and Cohen (1998) postulated bottom-up factors driving the embodiment of the rubber hand. In their view, proprioceptive information becomes biased to match sensory information from vision and touch. Scientific evidence supports the contribution of bottom-up factors in the RHI (e.g., Guterstam et al., 2019) and in VR (e.g., Slater et al., 2010b). Top-down factors can likewise influence embodiment by limiting the scope of integration into one's own body. Thus, factors like shape (e.g., Tsakiris et al., 2010) and orientation (e.g., Ehrsson et al., 2004) of the rubber hand are important constraints. This indicates that the embodied entity should be plausibly connected to the body, although some degrees of flexibility can be observed (e.g., Kilteni et al., 2012b). The relevance of individual factors was recently examined, indicating that having control and a first-person-perspective over an avatar in VR are more important for embodiment than avatar appearance (Fribourg et al., 2020).

Neurocognitive models of ownership also consider bottom-up and top-down factors. Tsakiris (2010) describes a three-step comparison underpinned with neural correlates contributing to the RHI. The first two steps compare the appearance and posture of the rubber hand to top-down knowledge of one's own body. Bottom-up sensory information (e.g., seeing a rubber hand being touched and feeling touch on one's own hand) are compared in a third step, enabling participants to feel the brush strokes on the rubber hand, and to attribute ownership to the rubber hand. Although this model is specific for the RHI, it could in principle be applied to embodiment experiments in VR. Maselli and Slater (2013) proposed that ownership may arise from the interaction of different neural populations encoding top-down and bottom-up influences. Hereby, one population of neurons encodes the similarity between virtual and real hand, leading to the feeling of ownership, whereas neurons sensitive to multisensory information modulate the feeling of ownership. Thus, top-down restrictions have to be met before multisensory correlations can affect participants' feeling of ownership. On a computational level, embodiment can be applied to Bayesian causal inference (Kilteni et al., 2015; Samad et al., 2015). In this framework, an artificial body part becomes integrated into one's own body when a common cause for multiple sources of information can be inferred, e.g., during synchronous visuotactile stimulation. This formulation can also integrate top-down knowledge, which, together with bottom-up factors, affects the likelihood in the Bayesian inference (Kilteni et al., 2015). Altogether, the different formulations and models have in common that they describe ownership to arise as a consequence of both bottom-up and top-down factors.

Agency is commonly described in a prediction framework, e.g., the comparator model. In this model, agency over actions (based on motor commands) is experienced when the predicted movements (based on efference copy signals) match the sensory feedback associated with that movement, i.e., when no prediction error occurs (Haggard, 2017). Actions are obviously the core element of agency, but they can also be linked to ownership and presence. On the one hand, the representation of actions depends on the classification of the hand as being part of the self or the other (Uhlmann et al., 2020), which suggests that ownership of a body part is important for the representation of actions, and therewith agency. On the other hand, acting in an environment was also suggested to be a crucial element for the sense of presence (Zahorik and Jenison, 1998). In this view, one can only feel present in an environment if one can act in this environment. This link was also emphasised by a model of Seth and colleagues (Seth et al., 2012) that draws parallels between presence and agency. The model describes presence in a predictive coding framework (c.f., Rao and Ballard, 1999), interacting with agency. Presence occurs from comparing predictions of interoceptive information to the actual interoceptive information. As a result, acting in an environment might link the agency component of embodiment and presence.

Presence can be manipulated by various factors, which can broadly be divided in manipulations of the display content, e.g., the avatar or the virtual environment, and hardware properties of the mediation technology, e.g., the HMD. Participants' VR experience seemed to benefit from having a virtual body in a realistically rendered environment, in which other avatars respond to the participant (Llobera et al., 2021). Although this study did not explicitly investigate presence, the investigated factors were relevant for presence in previous studies (Slater et al., 2010a; Steed et al., 2018). In addition, wearing an HMD with a wide field of view supports participants' feeling to be in the virtual environment (Slater et al., 2010a; Buttussi and Chittaro, 2018) and their belief that events in this environment are actually happening (Slater et al., 2010a). Similarly, removing motion parallax, which is a depth cue we normally experience in everyday life, decreased presence (Eftekharifar et al., 2020). Many of those factors relate to the properties of the device, which resembles the definition of immersion as properties related to the technology (Slater and Wilbur, 1997).

It was postulated (Bystrom et al., 1999) that immersion determines how much the virtual environment resembles the real environment. For presence to emerge, participants need to direct their attention to the sensory information provided by the technology. As a consequence, they might start to treat the virtual environment as real, which enables participants feeling to be within the virtual environment. Similar ideas have been put forward (Wirth et al., 2007), suggesting that directing attention towards the provided sensory information (e.g., from an HMD) is necessary for the construction of a spatial representation of one's environment. Spatial presence arises when participants incorporate the spatial reference frame of the virtual environment instead of the one provided by the real environment. Altogether, immersion and attention seem to be core concepts for presence.

In sum, the suggestion of multifaceted interactions between embodiment and presence require a common consideration of both processes (Kilteni et al., 2012a; Nostadt et al., 2020). Relating ourselves to the body on the one hand, and the body to the environment on the other hand, might create a link between embodiment and presence (c.f., Kilteni et al., 2012a). This link might be provided by the body schema, i.e., an unconscious model of the body and its parts (c.f., Maravita and Iriki, 2004). It was argued that the body schema adjusts by incorporating the technology (e.g., the HMD), as a consequence giving access to a virtual environment similar to our natural environment. It thereby enables participants' feeling to be within the virtual environment (Haans and IJsselsteijn, 2012). Nevertheless, a conceptualisation of a common framework is still missing.

2 A COMMON FRAMEWORK OF EMBODIMENT AND PRESENCE

At the current stage of research, a precise characterisation of embodiment and presence is still missing. Given the possible overlap and interdependencies between the two constructs, we believe that an agreed-upon, formal definition is needed to move the field forward. Here, we propose a conceptual framework of embodiment and presence, the Implied Body Framework (IBF, **Section 2.1** and **Section 2.2**). Presence is thereby conceptualised as the sense to "be there" (e.g., Slater and Steed, 2000; Slater et al., 2010a). The IBF aims to integrate current findings and allows to derive new and testable hypotheses (**Section 2.3**).

2.1 The Implied Body Framework

Multisensory integration (e.g., Botvinick and Cohen, 1998; Guterstam et al., 2019) is a key component in the IBF (**Figure 2**). We assume that multisensory information indicates the (possibly implicit) presence of a body, which we call *implied body*. An implied body is inferred from multisensory correlations. For example, visuomotor correlations between head movements and changes in the visual scene, give rise to an implied body. This shows that the implied body does not require the representation of a (virtual) body (c.f., Guterstam et al., 2015); any multisensory correlation will be sufficient (c.f., Ehrsson et al., 2005; Kalckert and Ehrsson, 2014b). Plausible implied bodies (c.f., Tsakiris, 2010) are integrated into the body representation (Implied body 1 and 2). In this step, the implied body is, for example, assessed with respect to its shape (e.g., Tsakiris et al., 2010), orientation (e.g., Ehrsson et al., 2004), and distance (e.g., Kalckert and Ehrsson, 2014b) from the existing body representation. Embodiment of an entity arises from integrating implied bodies into the body representation, whereas presence relates to the spatial reference point of this body representation.

We propose that multisensory integration can enhance or impede the strength of the body representation by 1) weighting

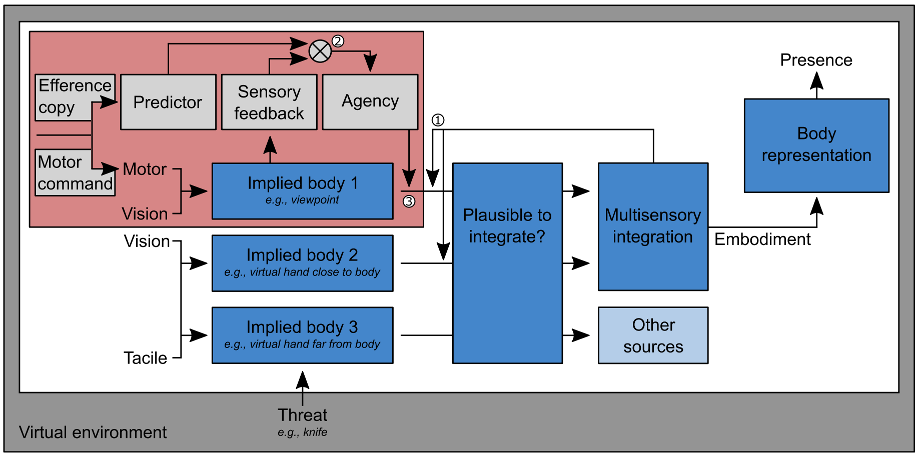

FIGURE 2 | The Implied Body Framework (IBF). Embodiment and presence emerge from integrating multisensory signals related to implied bodies. Hereby, multisensory correlations indicate implied bodies. If implied bodies are plausible, multisensory integration links the multisensory correlations into the body representation. As a consequence, entities like a virtual hand can be embodied. Presence arises in connection to the spatial reference point of the body representation. The multisensory integration process also 1) feeds back to the individual implied bodies, making it more likely that the multisensory information becomes integrated in the next iteration. If an implied body is not plausible, it will be experienced as disconnected from one's own body and multisensory correlations are attributed to other sources. Agency arises from 2) comparing predicted movements to sensory feedback. It is directly linked to some of the implied bodies, 3) increasing the likelihood that sensory signals are passed on to the multisensory integration process. Threat is directed against the implied bodies.

implied bodies (**Figure 2**, feedback arrow). Implied bodies with an increased weight are more likely to pass the plausibility check and to be integrated during the next iteration; thereby strengthening the body representation in the respective environment. A change in the body representation will also affect how strongly we feel present in the respective environment (c.f., Slater et al., 2010a). This effect should be especially strong when multisensory integration enhances or impedes implied bodies which are an important cue for a spatial reference point in the environment. The viewpoint (Implied Body 1) is the visual origin and determines the perspective a participant has in the virtual environment, thereby giving a spatial reference point for where we are located in the environment. Integrating the implied body related to the viewpoint might therefore be especially important for presence (c.f., Gorisse et al., 2017).

According to the IBF, different multisensory correlations lead to different implied bodies. For example, visuomotor correlations create an implied body related to the viewpoint of the participant (Implied body 1), and visuotactile correlations create a second implied body related to a virtual hand being stroked by a brush (Implied body 2). As only plausible implied bodies become integrated, an implied body from multisensory correlations linked to a virtual hand placed far away from one's own body (Implied body 3) is not integrated into the body representation (c.f., Kalckert and Ehrsson, 2014b). This virtual hand would be perceived as disconnected from one's own body, and the tactile sensations as caused by another source. Such a phenomenon has been described for somatoparaphrenia (c.f., Jenkinson et al., 2013), where the real arm becomes not integrated with the rest of the body. We propose that multisensory information is integrated in a way that maximises the evidence of the resulting body representation. This is similar to hierarchical Bayesian frameworks, where an artificial hand becomes integrated based on the collected evidence from multisensory correlations (Kilteni et al., 2015; Samad et al., 2015).

Agency (**Figure 2**, red box) can facilitate the emergence of implied bodies. Actions generate motor input to implied bodies (e.g., as part of visuomotor correlations). In this case, sensory feedback arises from the implied body (Implied Body 1), which is 2) compared to the predicted sensory consequences of the movement, leading to agency when no prediction error occurred (c.f., Haggard, 2017). The status of an implied body is important for agency (c.f., Uhlmann et al., 2020), as it facilitates the feeling to be in control over one's own body. In addition, experiencing agency indicates that the implied body belongs to one's own body (c.f., Tsakiris et al., 2006), and it is therefore more likely that it will be integrated with the other implied bodies. Thus, agency interacts with the implied bodies. Most relevant for the body representation is that agency can 3) moderate the processing of the implied bodies, thereby influencing their integration into the body representation.

2.2 The Implied Body Framework Applied to the Virtual Rubber Hand Illusion

To illustrate the IBF, we apply it to a virtual reality RHI experiment (**Figure 3**). The participant (**Figure 3**, left) sees a virtual environment using an HMD through which real head movements lead to an updated visual input, similar to what is experienced in real life. These multisensory signals create an implied body (**Figure 2**, Implied body 1). The head movements are self-generated and based on predictive mechanisms (**Figure 2**, red box), leading to a sense of agency, which makes it more likely that the implied body connected to those movements gets further processed. In addition to the visuomotor correlations leading to

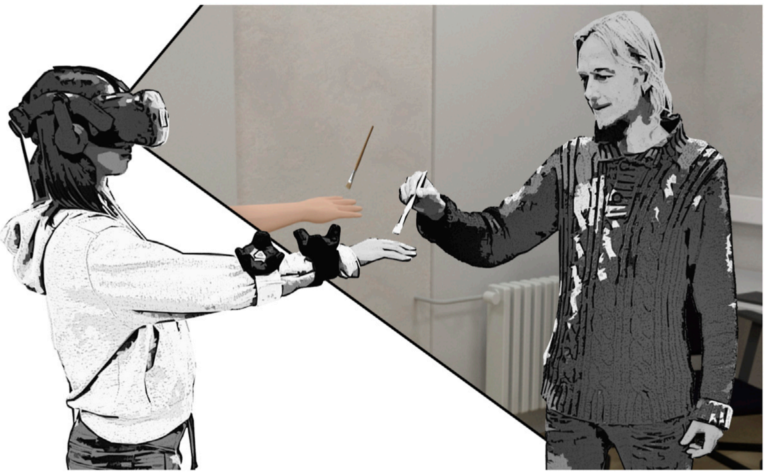

FIGURE 3 | Example of a virtual RHI setup. The black and white area depicts the participant (left) and experimenter (right) situated in the real environment. The coloured area represents the virtual environment, which the participant perceives via an HMD. When the experimenter stimulates the participant's real hand with a brush, the participant sees these brush strokes on a virtual hand in VR. The virtual hand model was taken from turbosquid.com under their standard license.

the first implied body, the participant also experiences visuotactile correlations (Implied body 2). The participant sees how a virtual hand close to the viewpoint in VR, is stroked by a virtual brush, while the experimenter (**Figure 3**, right) is physically stroking the participant's real hand. Both implied bodies are plausible, and their close proximity indicates that they originate from the same body. The multisensory information is therefore integrated, embodying both implied bodies in a body representation. The feeling of the virtual hand as belonging to the own body emerges. This body representation has a spatial reference point, whereby integrating the visuomotor signals into the body representation gives a strong cue of where one is located in the environment. A sense of spatially belonging to this environment emerges, i.e., the participant feels present in the virtual environment. This suggests that what is commonly reported as presence depends upon (at least implicitly) a body.

2.3 Deriving Hypotheses From the Implied Body Framework

2.3.1 Plausibility Only Affects Implied Bodies From Synchronous Multisensory Correlations

The basic assumption of the IBF is the existence of implied bodies. The model suggests that implied bodies can only arise from synchronous multisensory correlations. Implied bodies are integrated into the body representation, if they are plausible, e.g., when the virtual hand resembles the participant's hand. An implied body cannot emerge from asynchronously stimulating the participant's hand and a virtual hand. In this case, the implied body will be rejected from integration before passing the check for plausibility. Consequently, the shape of the stimulated virtual hand should be irrelevant, yielding the same results for a realistic hand model or a cube, if asynchronous stimulation was used. However, for synchronous stimulation we would expect that the shape of the simulated hand is important. Thus, although a certain similarity to the participant's hand is necessary (Tsakiris et al., 2010), personalisation should further increase embodiment (c.f., Waltemate et al., 2018).

2.3.2 Agency Influences the Weight of Implied Bodies

Agency interacts with the implied bodies depending on the motor input. Thereby, the sensory feedback comes from the implied body and is compared against the motor prediction, resulting in agency if no prediction error occurred. Agency again modulates the weight of the implied body, before it reaches the plausibility check. This has two implications. First, agency and embodiment can be dissociated when agency over a limb is experienced, but the implied body did not pass the plausibility check. This is for example the case when a rotated rubber hand moves in accordance with one's own hand (c.f., Kalckert and Ehrsson, 2012). Second, we would expect that agency hinders or facilitates embodiment depending on the paradigm. For example, agency should sensitise participants for spatial offsets between their hand and an artificial hand (c.f., Kalckert and Ehrsson, 2014b). At the same time, agency might increase the likelihood that the implied body passes the plausibility check, e.g., when the shape of the virtual hand does not fully match.

2.3.3 Feedback From Multisensory Integration Stabilises the Body Representation

When the implied body passes the plausibility check, multisensory integration will link the sensory information, thereby integrating the implied bodies into the body representation. The IBF postulates that multisensory integration scales the weight of the implied bodies, which makes it more likely that the same implied body is part of the body representation in the next iteration. Therefore, the IBF predicts that the embodiment of an entity is not immediately disrupted when the multisensory correlations break down, but slowly declines (c.f., Pfister et al., 2020).

2.3.4 Presence Depends on Embodiment

The embodiment of implied bodies constitutes a body representation, to which presence relates. The IBF therefore understands presence as depending on embodiment processes. Presence cannot arise without at least a basal form of embodiment. If participants feel present when a virtual body was not presented to them, it likely goes along with a basal form of embodiment, e.g., for the implied body from the viewpoint. This dependence suggests that both processes are correlated. However, the direction of the dependence also predicts that there might be situations where participants feel embodied, but not present.

2.3.5 Physiological Measures Confound Embodiment and Presence

A relevant sensory event, e.g., threatening the virtual hand with a knife, can lead to a physiological response, which allows us to measure embodiment and presence or, more specifically, the impact of threat on the implied bodies (**Figure 2**, Threat). Threat can thereby only elicit a physiological response when the implied body is part of the body representation. Threatening Implied Body 1 or 2 should therefore lead to a physiological response, contrary to threatening Implied body 3. As embodiment and presence depend on the implied bodies, the IBF suggests that it is not possible to separate both processes based on physiological measures related to threat. However, as embodying implied bodies directly constitutes to the body representation, embodiment might be more closely connected to physiological measures than presence.

3 DISCUSSION

Previous work suggests a relation between embodiment and presence. To characterise this relation, we proposed the Implied Body Framework (IBF). This framework postulates the existence of implied bodies, which can be integrated in a body representation, based on multisensory integration. Presence depends on this body representation and therewith on embodiment processes. In the following section, we compare our model to previously introduced models on embodiment and presence (**Section 3.1**). The IBF provides an important step towards a common consideration of both processes. However, embodiment and presence research might still be prone to different limitations and confounds, which need to be considered. We will therefore conclude by discussing the impact of two important factors that challenge embodiment and presence research: attention (**Section 3.2**) and biases (**Section 3.3**).

3.1 Comparing the Implied Body Framework to Existing Models

Similar to existing frameworks (Tsakiris, 2010; Maselli and Slater, 2013), the IBF considers bottom-up (multisensory correlations leading to implied bodies) and top-down influences to be important. As part of top-down influences, implied bodies are checked for their plausibility (e.g., taking the orientation of the virtual hand into account). Compared to previous models, the IBF inversed this order, i.e., only objects providing multisensory correlations are checked for plausibility. This should reduce the computational costs, because otherwise every potential object in the environment would have to be assessed as a potential body part. Increasing the weight of implied bodies by the multisensory integration process can thereby prevent that body parts which do not provide multisensory correlations, are immediately removed from the body representation. In other words, the body representation is stabilised. This influence of multisensory integration on the implied bodies could be described by an updated prior distribution in a Bayesian framework (c.f., Kilteni et al., 2015).

Participants can have a body representation without visually being presented with a body, e.g., an avatar. The implied body from participant's viewpoint is likely the most important factor for presence; and similarly for embodiment (c.f., Maselli and Slater, 2013). In case of an invisible body, this implied body could be combined with other implied bodies, which are not visual in nature. For example, motor information can still be correlated with observed effects in the environment (e.g., stretching an invisible arm to move a mug) or their tactile consequences (e.g., stretching an invisible arm and feeling the touch of a mug). In addition, we would receive proprioceptive information of our body. Using VR without a virtual body should therefore lead to the feeling to own an invisible body (c.f., Guterstam et al., 2015), accompanied by a feeling of presence in the virtual environment.

Importantly, the IBF closely links presence to embodiment processes by postulating the importance of implied bodies and the body representation for presence. A link of presence to embodiment by incorporating the mediation technology into the body schema was suggested previously (Haans and IJsselsteijn, 2012). The IBF expands on this idea and argues for a direct link between embodiment and presence, based on implied bodies and the body representation. We therefore expect both processes to be positively correlated (c.f., Roth and Latoschik, 2020).

The spatial reference point of the body representation is central to link embodiment and presence. In contrast to a previous model by Wirth et al. (2007), the IBF argues that the spatial reference point to which presence refers to, depends on the implied bodies and the body representation, of which the body is a part, as compared to the spatial reference point encompassing the body itself. Locating ourselves in relation to the body or the environment therefore relies on the same spatial reference point. We will always feel present at this spatial reference point and, at least in most situations, this will be within the body.

A manipulation of the perspective over an avatar, i.e., changing a first-person-perspective to a third-person-perspective, can therefore decrease embodiment, but leave presence unchanged (c.f., Gorisse et al., 2017). Changing the viewpoint to a position outside the virtual body presents participants with an unexpected configuration for a body representation. There is no such conflict for presence, because the viewpoint is a strong location cue, leading to the feeling to be present outside of the own body.

The IBF integrates the comparator model of agency (c.f., Haggard, 2017). Agency is a separate process, interacting with the implied bodies. On the one hand, separate processes for agency and embodiment are in line with findings suggesting a dissociation between agency and ownership (c.f., Kalckert and Ehrsson, 2012). On the other hand, interactions between agency and the implied bodies could explain why embodiment can be induced by visuomotor correlations (e.g., Kalckert and Ehrsson, 2014a). Such motor signals are self-generated, which might have the benefit that attention towards those signals is not necessary to experience them. This is in contrast to other sensory correlations, which might need to be attended for embodiment and presence to emerge.

Immersion (c.f., Bystrom et al., 1999) and attention (c.f., Bystrom et al., 1999; Wirth et al., 2007) were previously proposed to be important for presence. Although the IBF does not directly emphasise these factors, it does not contradict this notion. Immersion is relevant in the context of VR and other mediation technology, while attention is directly relevant in the selection of sensory information. These processes can thereby significantly influence which entities are embodied and where we feel present.

3.2 Attention

Attention is a mechanism which optimises the precision of sensory inputs (Friston, 2009) and can thereby influence, which information enters the multisensory integration process. However, multisensory integration can also facilitate stimulus detection, which links attention and multisensory integration, bidirectionally (Talsma et al., 2010). The selected sensory information is thereby crucial for embodiment and presence.

Healthy humans have an ever-present sense of embodiment over their own limbs, without having to consciously and constantly pay attention to this feeling. The same is true for the sensation to be present within the environment. The question arises, whether humans have to actively attend to multisensory signals (e.g., congruent information from vision and touch) to experience embodiment and presence in experiments like the virtual RHI. One might predict that it would be unlikely for both processes to arise, when attention is drawn away from the virtual body or the virtual environment. Attention could therefore serve as a gateway that enables embodiment and presence. Investigating the effects of attention could provide further insights into the relation between the self, on the one hand, and the body or the environment, on the other hand.

Case studies on somatoparaphrenic patients can provide first evidence for a crucial role of visuospatial attention in the processing of one's own body (Fotopoulou et al., 2011; Jenkinson et al., 2013). Somatoparaphrenic patients perceive a body part as belonging to someone else. Presenting the patient's arm in a mirror helps to recognise the disowned arm as the own one by presenting the visual feedback of the body from a third-person perspective (Fotopoulou et al., 2011). This suggests that ownership over the hand does not only depend on seeing one's own body, but also on the information one is attending to. For example, attending to one's extrapersonal space seems to improve the patient's recognition of her own arm, probably due to enhanced processing of the body from a third-person-perspective (Jenkinson et al., 2013). An RHI experiment with healthy controls showed that seeing the rubber hand in a mirror did not affect the strength of the RHI (Jenkinson et al., 2013). However, experiencing touch on the rubber hand benefitted from attending the rubber hand compared to the real hand. Altogether, this suggests that attention may support the occurrence of embodiment by selecting which body-related information (e.g., from first-person-perspective or third-person-perspective) is further processed. This seems to be especially relevant in the context of disorders such as somatoparaphrenia, where attention can promote body self-recognition (Jenkinson et al., 2013). The importance of attention to select sensory input is in line with the IBF.

Attention could be considered as an integral component of presence. To feel present in a virtual environment requires to attend to the stimuli from that environment. Accordingly, switching ones attention from the virtual to the real environment could account for breaks in presence (c.f., Slater and Steed, 2000). Arguably, presence will increase if participants pay attention to the virtual environment (Bystrom et al., 1999), and decrease when distractions, for example noise from the laboratory, are present (see **Box 2**). In line with the IBF, this suggests that attention can affect presence, which is also supported by the theoretical conceptualisations (Bystrom et al., 1999; Wirth et al., 2007), and the underlying factors influencing presence in the presence questionnaire (Witmer and Singer, 1998). In this questionnaire, involvement (one of the key factors underlying presence) is directly related to attention. Hereby, attention influences involvement, which again influences the degree of perceived presence.

If presence depends on attention, one would expect that detecting stimuli from the real environment is attenuated, when the participant feels present in a virtual environment. Accordingly, electrophysiological recordings show that participants experiencing higher presence (physical-, social-, and self-presence) in a desktop game showed lower amplitudes of attention-related event-related potentials (N1 and mismatch negativity) in response to sounds presented in the real environment (Terkildsen and Makransky, 2019). This suggests that participants allocated more attention towards the desktop game, and not towards the external distracting stimuli, which in turn facilitated the feeling of presence. A similar mechanism was also proposed to explain an effect from presence on memory. The authors argued that attention elicits and sustains presence, whereby presence also increases attention towards stimuli from the virtual environment, resulting in attenuating distracting stimuli from the real environment (Makowski et al., 2017).

In line with the IBF, attention is especially relevant for the selection of sensory information. Attention can influence the weighting of sensory information and thereby determine the integration of multisensory information related to the body

BOX 2 | Open Research Questions.

Can visuomotor correlations from head and eye movements be sufficient to induce embodiment and presence? The introduced Implied Body Framework (see **Section 2**) assumes that multisensory correlations (e.g., visuomotor correlations while moving one's head) lead to the sensation of a body; a sensation that does not need to be visual in nature, i.e., the body is implied. In VR and RHI experiments, participants are allowed to move their head and perceive an updated visual scene. The significance of such visuomotor correlations can be tested as follows: Participants are presented with a virtual environment while all movements, including eye and head movements, are restricted. Embodiment and presence ratings are compared to a second condition, in which they can move their eyes, and a third condition, in which they can move their eyes and head. We expect that participants' ratings increase with the amount of movement possible: no movement < eye movements < eye and head movements. In a fourth condition, participants fixate a cross at a fixed position on the HMD, i.e., relative to their head, so that their eye movements are fixed in space, but head movements are possible. This would allow to test for the role of eye or head movements on embodiment and presence ratings. In a control condition, participants view visual updates of the scene as a passive observer (no movement). This would inform about the importance of self-generated visual updates of the scene, independent of their origin (eye or head movements).

What alternative experimental methods can be used to measure embodiment and presence? One crucial step would be the development of questionnaires with strong psychometric properties that can be widely used in experimental tasks (c.f., Roth and Latoschik, 2020). These questionnaires need to be combined with additional experimental methods to further increase the validity of the measures and to avoid bias. For example, Chancel and Ehrsson (2020) showed that psychophysical measures of hand ownership are suitable to assess embodiment. In their setup, they presented two rubber hands to the participants. In a two-alternative forced-choice (2AFC) task, participants indicated over which of the two hands they felt ownership. The results show that this task can capture the influence of displacement of the rubber hand on reported ownership. It therefore provides a useful method to answer questions in embodiment and presence research (c.f., Chancel and Ehrsson, 2020; Chancel et al., 2021; Chancel et al., 2022).

Can the sensation of embodiment and presence be influenced by attentional capture? If embodiment and presence are influenced by attention, then it should be possible to increase or decrease the two by manipulating participants' attention. On the one hand, participants who feel present in an environment seem to dismiss distracting stimuli from the real world (see **Section 3.2**, Terkildsen and Makransky, 2019). Games like Beat Saber (Beat Saber, Prague) could be used to manipulate the attentional focus by requiring actions in response to stimuli which vary in speed. On the other hand, interfering noise which captures attention should have an adverse effect on embodiment and presence. To test this, distracting stimuli can be introduced which can be ascribed to the laboratory (an experimenter speaking) or the virtual environment (an experimenter speaking who is represented by an avatar).

Are results on embodiment and presence affected by demand characteristics and suggestibility? Demand characteristics and suggestibility are a serious challenge to embodiment and presence research, as outlined above (**Section 3.3**). So far, demand characteristics have only been investigated for embodiment, but not for presence, where one can apply the same critique. It is important to uncover the role of demand characteristics by using control experiments (Orne, 1962; Lush, 2020). A comparison between an experiment in the laboratory and an experiment in which participants rate their expected sensations after observing another participant performing this experiment, could provide further insides (Orne, 1962). Following a recent approach, suggestibility could be measured by rating experiences during made-up exercises, like imagining acoustic and tactile sensations of a mosquito (Lush et al., 2021a).

representation (Limanowski and Friston, 2020). In addition, multisensory integration might link attention and presence: it is known that attention can guide information selection for multisensory integration (Alsius et al., 2007) and presence can benefit from multisensory information (Marucci et al., 2021). Thus, multisensory integration might function at the intersection between attention and presence.

3.3 Methodological and Conceptual Biases

Comparing results from studies on embodiment is a challenging task, as standardisations, e.g., in the design, are missing (Riemer et al., 2019). This could be improved by standardising procedures, e.g., using stimulation devices (Sivasubramaniam et al., 2021). Yet, participants' responses can still be biased in various ways (e.g., regression to the mean, framing of instructions, or the good-subject effect). To detect biases, researchers often use two sets of items in embodiment research: illusion and control items. For the former, participants rate the extent to which they experienced the illusion. With control items, participants are always expected to give low ratings, because they describe phenomena not expected to occur as a consequence of the experimental manipulations. Similar responses to illusion and control items indicate that participants might show a response bias. An example of a control item is "It seems as if I had more than one right hand" (Kalckert and Ehrsson, 2012, p.4), a sensation which is not expected to appear during the experiment. However, reports of "having more than one right hand" (Ehrsson, 2009; Fan et al., 2021) imply ownership over an additional hand, which questions the validity of such control items. Further, it is arguable whether participants might be able to distinguish control items from illusion items (Lush, 2020), which would introduce a bias even though it was controlled for.

Bias might not be immediately obvious, especially when it produces results in accordance with the hypotheses. In this context, demand characteristics describe the hints passed on to participants which directly relate to the underlying hypotheses (Orne, 1962; Lush, 2020), although this does not necessarily mean that participants guess the hypotheses correctly (Corneille and Lush, 2022). Perceiving demand characteristics can encourage participants to confirm experimental hypotheses (Nichols and Maner, 2008). It is therefore important that experiments are designed in a way to prevent such biases. Normally, experimenters try to hide the hypotheses of their experiments from participants to minimise any kind of hypotheses-confirming behaviour. However, there are a number of ways how experimental hypotheses can become known, including the experiment itself (Orne, 1962). For embodiment and presence research, one might argue that the aim of the study becomes obvious when participants are confronted with the questionnaire items (c.f., Reader, 2022). It might be easy to guess at experimental manipulations, for example, a sensation to own a virtual body, and whether this sensation should be enhanced or decreased. To avoid any drawbacks from demand characteristics, participants could be asked about the purpose of the experiment afterwards (Orne, 1962). Another possibility is the design of an additional experiment that only describes the experimental procedures and then assesses the participants' expected response on the same experimental measures (Orne, 1962). While the first option might invalidate the experimental approach, the second option can directly test if the experimental design is prone to demand characteristics. The latter approach was recently followed up in a study that examined the effect of demand characteristics in the RHI (Lush, 2020). In an online experiment, participants watched a video and read the descriptions of a typical RHI experiment, and then filled out one of the frequently used RHI questionnaires. The results of this experiment were similar to the results revealed in other RHI studies, which indicates that participants were indeed able to correctly guess the purpose of the experiment, even when they were absolutely naïve about the experimental interests (see also, Lush et al., 2021b; Reader, 2022). Therefore, it is likely that previous results are affected by demand characteristics questioning their validity.

Suggestibility, i.e., participants liability to experience induced sensations, might govern their perception (as well as the associated behaviour and measured responses) in accordance with the research hypotheses (Lush, 2020). In other words, participants' susceptibility to respond to the perceived demands and to change their experience accordingly can influence, and even predict the extent of the RHI (Lush et al., 2020; Roseboom and Lush, 2022). This effect of suggestibility can be observed for questionnaires (Marotta et al., 2016; Fiorio et al., 2020; Lush et al., 2020) and proprioceptive drift (Walsh et al., 2015; Fiorio et al., 2020; Lush et al., 2020). However, these effects are not always replicated for all measures (Walsh et al., 2015; Marotta et al., 2016), which might depend on differences in the measures or the experimental design. These results show that suggestibility can affect results in embodiment (and likely presence) experiments, possibly even without reaching awareness (for an ongoing debate, see Ehrsson et al., 2022; Lush and Seth, 2022).

To reduce the confounding effects of demand characteristics and suggestibility on embodiment and presence, effective control measures are needed (Lush, 2020). Commonly used control items and measures known to be objective (e.g., electrodermal activity and proprioceptive drift) might be insufficient (Lush et al., 2021b). It is therefore important to explore how research methodology can be further improved (**Box 2**).

4 CONCLUSION

More than 20 years after the first influential paper on the RHI (Botvinick and Cohen, 1998), we are closer than ever to applying the concepts of embodiment and presence to rehabilitation, training, or gaming purposes, especially due to the rise of virtual reality technology. However, the lack of a common framework, valid measures, and bias-free designs pose a serious challenge. We are at the cusp of deciding which direction to take in embodiment and presence research. The large amount of overlap concerning theory and findings in embodiment and presence literature makes the case for a common framework. To this end, we introduced the Implied Body Framework (IBF). This framework proposes that multisensory signals can constitute multiple implied bodies, which can be embodied into one body representation. This body representation provides a spatial reference point for presence. With the IBF, we aim to foster new perspectives for future research and their application.

AUTHOR CONTRIBUTIONS

PPF and HK conceptualised the Implied Body Framework. PPF provided an initial draft and wrote the manuscript. HK and KF revised and wrote the manuscript. PPF designed and created, HK revised the figures.

FUNDING

This work was funded by the German Research Foundation, International Research Training Group, IRTG 1901, "The Brain in Action" and by "The Adaptive Mind", funded by the Excellence Program of the Hessian Ministry of Higher Education, Research, Science and the Arts.

ACKNOWLEDGMENTS

We would like to thank Bianca Baltaretu for providing feedback to the manuscript and Meaghan McManus for feedback to the Implied Body Framework.

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2 Study II: Demand characteristics challenge effects in embodiment and presence

Forster, Karimpur, & Fiehler, 2022, *Scientific Reports*

scientific reports

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Demand characteristics challenge effects in embodiment and presence

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The sensations to own and control a body as well as being located in a body describe the relation between ourselves and our body, termed embodiment. Embodiment plays a central role in our everyday actions. However, its assessment is challenging. Recent findings suggest that measures on embodiment are confounded by demand characteristics and suggestibility. To investigate the impact of demand characteristics on embodiment and presence, we compared results from an online experiment measuring participants' expectations, to the same experiment in virtual reality (VR). In the online experiment, participants watched a video of a participant performing the VR experiment. In the VR experiment, participants performed a soap-bubble-kicking task, which allowed the feelings of embodiment and presence to arise. We manipulated temporo-spatial movement synchrony (Movement: synchronous, asynchronous) and avatar visibility (Visibility: visible, invisible). In addition, we assessed participants' suggestibility with exercises. The introduced manipulations influenced the ratings in both experiments similarly. Embodiment ratings were additionally affected by suggestibility. Altogether, our results show that participants were aware of the research hypotheses, which indicates that demand characteristics confound embodiment and presence research alike. Overcoming challenges of demand characteristics is crucial to correctly interpret scientific results and to translate these results into applied settings.

Regardless of the motor task we perform, from fine-tuned motor skills when playing an instrument to simple actions like pressing a key, we experience a direct relation to our body. This relation can be described as the feeling to own a body, to have a certain location relative to this body, and to be in control of its actions, defined as embodiment[1]. The rubber hand illusion (RHI) is frequently used to investigate embodiment. In this illusion [c.f.,[2]], participants see brush strokes on a rubber hand in front of their body, and perceive synchronous tactile feedback on their real hand, hidden from view. It is generally believed that embodiment emerges from the integration of multisensory information, in particular, visual information of the rubber hand and somatosensory information of the own hand[2,3]. In addition, specific constraints, like shape[4,5] and orientation[4,6], of the embodied rubber hand must be satisfied for embodiment to emerge. At the same time, body representations are also highly flexible. For example, virtually switching the left and right hand while interacting with a ball did not prevent the feeling of ownership to arise[7]. However, previous investigations on embodiment have recently been criticised to be influenced by factors not inherent to embodiment, namely demand characteristics and suggestibility[8,9].

Clearly, hypotheses should not be known to participants, as their knowledge can influence their behaviour[10]. Participants' expectations about what the experiment and the experimenter requires from them is known as demand characteristics[8,11,12]. Lush[8] argues that demand characteristics can at least partly explain results in RHI experiments. In his study, participants examined materials explaining the experimental setup and rated their expected sensations on an RHI questionnaire. Crucially, they did not participate in the actual experiment, but answered the questions on the sole basis of their knowledge about the experiment. The results were indeed similar to standard RHI experiments, suggesting that demand characteristics might influence the subjective ratings on the RHI.

Since then, several studies have suggested that demand characteristics play indeed an important role in embodiment research[13,14]. Even frequently applied objective measures like proprioceptive drift, i.e. the perceived drift of the real hand position towards the rubber hand, and skin conductance are argued to be subject to demand characteristics[13]. The critique of demand characteristics extends beyond mere RHI experiments to other paradigms and constructs. For example, measuring participant's simulator sickness before starting a virtual

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reality (VR) experiment increased simulator sickness scores when measured after the experiment[15]. However, demand characteristics do not always affect the results. Manipulating participants beliefs about the experimental hypothesis by providing differently framed instructions in an experiment on the facial feedback hypothesis did not abolish the effect[16]. It is therefore necessary to assess the extent to which demand characteristics influence subjective and objective measures, e.g. of embodiment.

On the one hand, demand characteristics could lead to a response bias, i.e. participants are consciously adjusting their responses to match the alleged expectations of the experimenter[10]. On the other hand, suggestible participants might be sensitive to unknowingly create experiences matching those of the perceived demands, which has been more recently described as phenomenological control[9,17]. In other words, knowing that ownership is expected to occur over a synchronously stroked rubber hand might lead to the sensation of ownership, because participants expect it to occur and unknowingly adjust their experiences accordingly. The concept of suggestibility is thus closely linked to demand characteristics, but different from imagination where participants are aware that they created these experiences by themselves[12]. According to this argumentation, participant's experiences could fall in line with the perceived demands, possibly, but not necessarily, matching the research hypotheses[12].

Previous work has shown that suggestibility can indeed predict results in embodiment experiments[9,18,19]. Whether and to what extent embodiment might depend on suggestibility is a matter of current debate[20,21]. Data pointing to suggestibility predicting embodiment[9] was recently questioned by a reanalysis[20]. In this reanalysis, the sample was divided into quartiles depending on their suggestibility scores. The illusion was produced in all four subgroups, i.e. also for participants scoring very low on suggestibility. This result suggests that embodiment cannot be explained solely on the basis of suggestibility. However, excluding suggestible participants from the sample makes it less likely to find positive RHI results[19]. Altogether, suggestibility might have an influence on results of embodiment although results in embodiment seem not to be reducible to suggestibility effects.

In this study, we investigated the influence of demand characteristics and suggestibility on embodiment. In addition, we wanted to test whether the same critique of demand characteristics can be applied to presence, which we conceptualised as the sense of "being there" in an environment [c.f.,[22]]. Similar to embodiment research, it might be easy for participants to predict the experimental purpose of questionnaires together with experimental manipulations used in presence research. Therefore, it is likely that demand characteristics could also affect the sense of presence. We constructed an experiment in which we combined embodiment and presence measures. To examine the influence of demand characteristics, we performed the same experiment twice[11]: once in an online version testing participants' expectations based on descriptions about the experiment without actually participating in the experiment, and once as a VR experiment where a second group of participants actively performed the task. In the online experiment, we presented the experimental manipulations to participants and let them rate their expected sensations of embodiment and presence. We constructed the VR experiment to have the exact same manipulations as depicted in the online experiment.

So far, presence has been mostly investigated in VR [e.g.,[23,24]]. Using VR enabled us to combine embodiment and presence in one single study. Comparing the results of the two experiments can further inform us if participants who only observed participants performing the VR experiment build expectations matching the responses of participants who actively performed the VR experiment. This would suggest that participants knew the research hypotheses and that their results could be affected by demand characteristics.

Methods

This study consisted of two independent within-subject experiments, an online and a VR experiment, with two independent groups of participants (combined analysis using a mixed design). To avoid carry over effects from the online to the VR experiment or vice versa we conducted the experiments in two independent samples. The online experiment was run as an online version of the VR experiment by showing videos of a participant performing the VR experiment in the laboratory. Based on the videos, participants rated their expected experience on selected questionnaire items [c.f.,[8,11]]. In the following, we will describe the VR experiment first, and then explain the specifics of the online experiment.

Experiment 1: Virtual reality.

Participants. We performed a power analysis (GPower 3.1.9.6,[25]) on pilot data (n = 13) to estimate the required sample size based on the effect of Movement on the ownership ($d_z = 1.01$), agency ($d_z = 1.24$), location ($d_z = 1.16$) and presence ($d_z = 0.47$) ratings. The power was set to 0.8 and the α error to 0.05. This resulted in a required sample of 9 participants for the effect of ownership, 9 for location, 8 for agency and 40 for presence. Our final sample consisted of 44 participants (26 females and 18 males), with a mean age of 24 years (SD = 3, ranging from 19 to 33). We sampled more participants than required based on the power analysis to ensure that at least 40 participants remained in the final sample after applying the exclusion criteria. Participants were recruited via university e-mail and received 8€ per hour or course credits. To participate in the experiment, participants had to be 18–35 years old, speak German fluently, have intact 3D vision and no poor eyesight (correction with soft contact lenses up to two dioptre were allowed). In addition, participants with pathological impairments of the sensory or motor systems or known neuropsychological disorders were not allowed to participate in the experiment. For one participant the avatar did not match in skin colour and for another participant the experimenter wrongly chose the sex of the avatar. As previous studies showed that embodying such unmatched avatars is possible[26,27], we decided to leave those participants in the sample. The experimenters followed the university's hygiene rules due to the COVID-19 pandemic. The Giessen University Ethics Committee approved the study and all participants provided written informed consent before beginning the experiment. The experiment was conducted in accordance with the Declaration of Helsinki (2004).

Figure 1. Virtual soap-bubble-kicking task and virtual presentation of the control and threat stimulus. (**a**) shows the soap-bubble-kicking task participants performed in VR. (**b**) shows the control (left) and threat (right) stimuli. Images are rendered from a third person perspective, but participants were always presented with the virtual environment from a first-person perspective. The avatar models are royalty free and taken from www.mixamo.com.

Setup. A Vive Pro Eye (HTC Corporation, Taoyuan City, Taiwan) head mounted display (HMD, 110° field of view, 1440 × 1600 pixels per eye, 90 Hz frame rate), trackers and a controller were used for the experiment. Skin conductance was continuously recorded at 2000 Hz with a BIOPAC MP36R system (BIOPAC Systems, Inc., Goleta, CA, USA). The virtual environment (Fig. 1) was modelled in Blender 2.93 and the experiment run in Vizard 6 (WorldViz, Santa Barbara, CA, USA). We modelled the virtual laboratory similar to the real laboratory. In the real laboratory, participants stood on the edge of a wooden plank. The plank was also presented in the virtual laboratory, both spatially coinciding. A gender matched avatar (Mixamo, as part of Adobe, San Jose, CA, USA) was used to represent the participant's body in the virtual environment. Six Vive trackers captured the motion of participants' arms, feet and torso. Participants held a Vive controller in their left hand to rate the questionnaire items.

Task and study design. Participants performed a soap-bubble-kicking task. In this task, they had to catch soap bubbles with their feet which burst after making contact (Fig. 1). As the soap bubbles always appeared in the lower field of view, spatial attention was generally directed downwards, i.e. in the area where the threat manipulation happened.

The experiment consisted of three within subject factors: *Movement* (synchronous, asynchronous), *Visibility* (visible, invisible), and *Threat* (threat, control). In the Movement condition, avatar movements were either temporo-spatially aligned with the participant's movements (synchronous), or temporo-spatially delayed by 30 frames (asynchronous). With asynchronous movements, all body movements except head movements were delayed, and this delay was well noticeable for participants. For Visibility, we either presented a fully motion-tracked avatar (visible), or hid the avatar from the participant's view by rendering it invisible (invisible). Threat was elicited by height exposure. A part of the floor dropped by 10 m with a speed of 5 m/s, leaving participants above the abyss on the virtual plank. An alert sound was played before the threat, followed by rumbling noise during the movement of the floor, indicating a machinery at work. We used a control stimulus and played the same sounds as with the threat stimulus, to control for confounding effects of visual and auditive attention [c.f.,[28]]. This consisted in a colour change of the area where the abyss was presented in the threat condition. The control stimulus was faded in and out, matching the temporal characteristics of the threat manipulation (videos of the different manipulations are depicted in the online material available at https://osf.io/3m4y8/).

All conditions were cross-combined, except for the asynchronous movements in the invisible condition, as it was judged to be infeasible to perform the soap-bubble-kicking task without a visual body representation when the own movements were delayed. Each participant completed six different conditions (visible-synchronous-threat, visible-synchronous-control, visible-asynchronous-threat, visible-asynchronous-control, invisible-synchronous-threat, invisible-synchronous-control). Visibility was blocked, and the block order was randomly determined. Trials within the Visibility blocks were likewise randomised.

We collected subjective measures of the embodiment components, i.e. ownership, agency, and location, by single item questions (see supplementary materials A). For this purpose, we adapted the items with the highest factor loadings of a previously used questionnaire[29]. In the invisible condition, we changed the wording from virtual body to invisible body. However, these items were only given to participants if they indicated that they had perceived an invisible body using a separate item (rating > 0). In addition to the skin conductance measure, we collected subjective fear ratings with a questionnaire item. The item on presence targeted the sense of "being there" in an environment, and was adapted from a another study[22]. For all six items (five on embodiment and presence, and one on the perception of an invisible body) we used a seven-point Likert scale ranging from 0 ("not at all") to 6 ("very much").

There are different measures to assess suggestibility[18,30–32]. We decided against the Sussex-Waterloo Scale of Hypnotizability (SWASH;[32]) because we did not want participant's reactions to be biased by their associations with hypnosis[33]. The phenomenological control scale (PCS;[31]), which is an adaptation of the SWASH without framing the exercises as hypnosis, was not officially published when preparing our experiment. We therefore used the *Sensory Suggestibility Scale* (SSS;[30]) which relies on comparable exercises containing sensory suggestions without the hypnotic context. This scale consists of 10 exercises, including sham items. An example for an exercise is the suggestion of having a sweet taste in the mouth, and for a sham exercise hearing rumbling noises when covering one's ears with the hands, i.e. a sensation which is truly perceived. We made adjustments during the translation of the scale to German. Some of those are based on the version used by Marotta et al.[18], others were made to ensure a better fit for testing the SSS online (see supplementary materials B for a description of all scenarios used in the German adaptation). Some exercises were difficult to perform in an online version at home because of the required materials (e.g., a standardised weight, which had to be held in the hand). We therefore selected a set of 7 exercises (2 sham), referring to items 1, 2, 3, 4, 5, 8, 10[30]. Participants rated their sensations on a rating scale ranging from 0 ("no sensation") to 4 ("very strong sensation"), whereby the labels were adjusted to fit the context of the exercise (e.g., "very strong sensation of a sweet taste"). To use the SSS in an online version, we prepared small video clips which explained and demonstrated the exercises, allowing participants to perform the exercises alongside. The order of the different exercises was randomised.

Procedure. Participants conducted an online survey after arriving at the laboratory. This survey was created to collect demographic data and conduct the SSS. Stereoscopic vision was tested with the Stereo Fly Test (Stereo Optical Co., Inc., Chicago, USA). Before starting the experiment, participants read the instruction for the VR experiment. We used a cover story which disguised the experimental purpose to measure the precision of VR motion tracking devices. Then, an experimenter equipped participants with electrodes for the skin conductance measure and fixed the Vive trackers to the participant's body. After the participant mounted the HMD, we calibrated the avatar to fit the size of the participant's physical body. We also adjusted the position of the virtual room so that the real and virtual plank coincided. The participant then performed the soap-bubble-kicking task. They started with either the visible (4 trials: synchronous-threat, synchronous-control, asynchronous-threat, asynchronous-control) or invisible (2 trials: synchronous-threat, synchronous-control) block. The threat or the control stimulus appeared after participants successfully caught 30 soap bubbles. The questions on embodiment (ownership, agency, location), presence, and fear were answered after each of the six experimental conditions. After finishing the VR experiment, participants did a post-experiment inquiry, which they again completed on their own. This inquiry included the Simulator Sickness Questionnaire (SSQ[34]) and questions about technical issues (e.g., tracking issues). The experiment had a total duration of about 90 min.

Experiment 2: Online. *Participants.* We used a mailing list to reach out to students of Justus Liebig University Giessen to participate in the online experiment. Participants could receive course credits or opt in for a lottery of a voucher. Only participants at least 18 years old and without known neuropsychological disorders were allowed to participate in the experiment. The final sample consisted of 111 participants (95 females, 15 males, and 1 diverse), with a mean age of 22 years (SD = 4, ranging from 18 to 59). We did not have pilot data to determine the required sample size by a power analysis. Because online data can be noisy and often have a high dropout rate, we decided to collect as many participants as possible in a one-month period. We informed participants that the online survey was in line with the Declaration of Helsinki (2004) and provided a button to give consent.

Study design. As in the VR experiment, participants in the online experiment first finished a survey on demographic data and then proceeded to the SSS. Experimental conditions were the same as in the VR experiment (see. 'Experiment 1: virtual reality.'). The only difference was that participants did not perform the task in VR. We explained to the participants in the online experiment that they would receive the instructions given to participants in the VR experiment. To further illustrate the VR experiment, we showed videos depicting the different conditions (see online material). After each video, participants answered the same questionnaire like in the VR experiment (see supplementary materials A). We asked participants to rate the questionnaire items as if they had participated in the VR experiment. Due to technical requirements, we did not block the Visibility condition like in the VR experiment, but randomised the presentation of all six conditions. At the end of the experiment, participants filled out a slightly adapted version of the post experiment inquiry used in the VR experiment (for example, tracking issues and the SSQ were only relevant in the VR experiment). Participants took about 40 min to complete the experiment.

Pre-processing and data analysis. *Exclusion VR experiment.* We excluded two participants from the sample, one because of not following the instructions and the other because of having participated in the pilot experiment. Due to technical difficulties (e.g., tracking issues), we excluded values from individual blocks for the different questionnaire items (4 participants with a total of 30 excluded values).

We introduced catch items during the SSS that were meant to detect participants which did not follow the instructions. These items required to summarise the instructions or to state important materials needed for the experiment. All participants passed these items. Catch items for each segment of the SSS were used to detect participants which did not follow the experiment attentively. Participants with a wrong answer on these items were excluded from the respective item(s), but left in the sample otherwise (2 participants with a total of 2 excluded values). Two questions during the SSS required participants to feel their pulse. Participants who stated that they were not able to do so were excluded from the respective items (5 participants with a total of 5 excluded values).

Exclusion online experiment. To detect participants in the SSS who did not read the instruction or did not follow attentively, we used a similar procedure as in the VR experiment. Two participants could not explain the instructions of the SSS and were removed from the analysis. Three participants answered the catch items used in each segment of the SSS wrongly and were excluded from the respective items (4 excluded values). In addition, participants who did not feel their pulse were excluded from the respective items (19 participants with a total of 29 excluded values).

Similar to the SSS, we used catch items to detect participants who did not read the instructions of the VR experiment. Five participants were not able to explain these instructions and were therefore removed from the analysis. We further introduced catch items to detect trials in which participants did not follow attentively by asking questions about the presented experimental manipulations. This resulted in 63 participants being excluded from respective items (658 excluded values, i.e. 17%).

Pre-processing and analysis. Pre-processing and data analyses were similar for the online and the VR experiment. Pre-processing and descriptive statistics were done in Python 3.8.5, statistical data analysis in RStudio 2021.09.0 with R 4.1.0. SSS scores were calculated relative to the total number of non-excluded items. Sham items were not used for the analysis. We used a linear mixed model (LMM) with the *lmer* function from the *lmerTest* package to analyse the data for each dependent variable separately. The model included a random intercept for each participant to account for the repeated measures design, and a fixed slope.

We used a difference coding for the categorical variables with coefficient −0.5 for online, asynchronous, invisible, control and coefficient 0.5 for VR, synchronous, visible, threat. Slopes therefore reflect the mean difference between the two factor levels. Positive slopes indicate higher ratings, and thus more pronounced effects, for the levels VR, synchronous, visible, and threat compared to their respective counter parts.

Model selection was done with the *step* function from the *lmerTest* package, which removes non-significant ($p \leq 0.05$) model components from a fully specified model (supplementary materials C). Study, Movement, Visibility, Threat, and their respective two-way interactions specified the full model (note that it is not possible to test for an interaction between Movement and Visibility). We used Maximum Likelihood (ML) to fit the models, which (as opposed to Restricted Maximum Likelihood, REML) seems to be beneficial when interested in the fixed effects[35], p. 29.

We assessed the model resulting from this selection process for outliers and influential cases, i.e. cases with studentised residuals outside the range of ± 3, or a cook's distance > 1. Only the criterium for the residuals was met for the questionnaire items (number of excluded values: ownership: 3; location: 4; agency: 6; presence: 4; fear: 5). To follow up interaction effects, we calculated individual models for the online and VR data set. We then compared the model slopes for the different predictors using a *Z*-test from the function *lm_slopes_compare* from the *EMAtools* package. This allowed us to compare the strength of the effect of our manipulations between the two experiments. For the suggestibility analysis we updated those follow-up models to include additional predictors.

Skin conductance. We used the skin conductance measure to assure that our height exposure manipulation lead to an increased experience of threat (see supplementary materials D). Due to technical issues, skin conductance was not recorded from one participant. We used a 0.05 Hz high-pass filter together with a threshold of 0.02 µS to preprocess the data. We considered skin conductance amplitudes within a 5.5 s window, starting 0.5 s after the event onset (alert sound preceding the threat or control stimulus by 0.5 s), as event-related skin conductance response. The amplitude of the skin conductance response was log-transformed: $\log_e(SCRAmplitude + 1)$. One value was excluded for having residuals outside the range of ± 3. The LMM fitted to the data showed that the threat compared to the control stimulus lead to a higher log-amplitude of the skin conductance response (95% CI in brackets after the slope, $b = 0.236$ [0.145–0.328], SE = 0.046, $t(126.068) = 5.092$, $p < 0.001$). This shows that the height exposure used in this experiment elicited a fear response in participants.

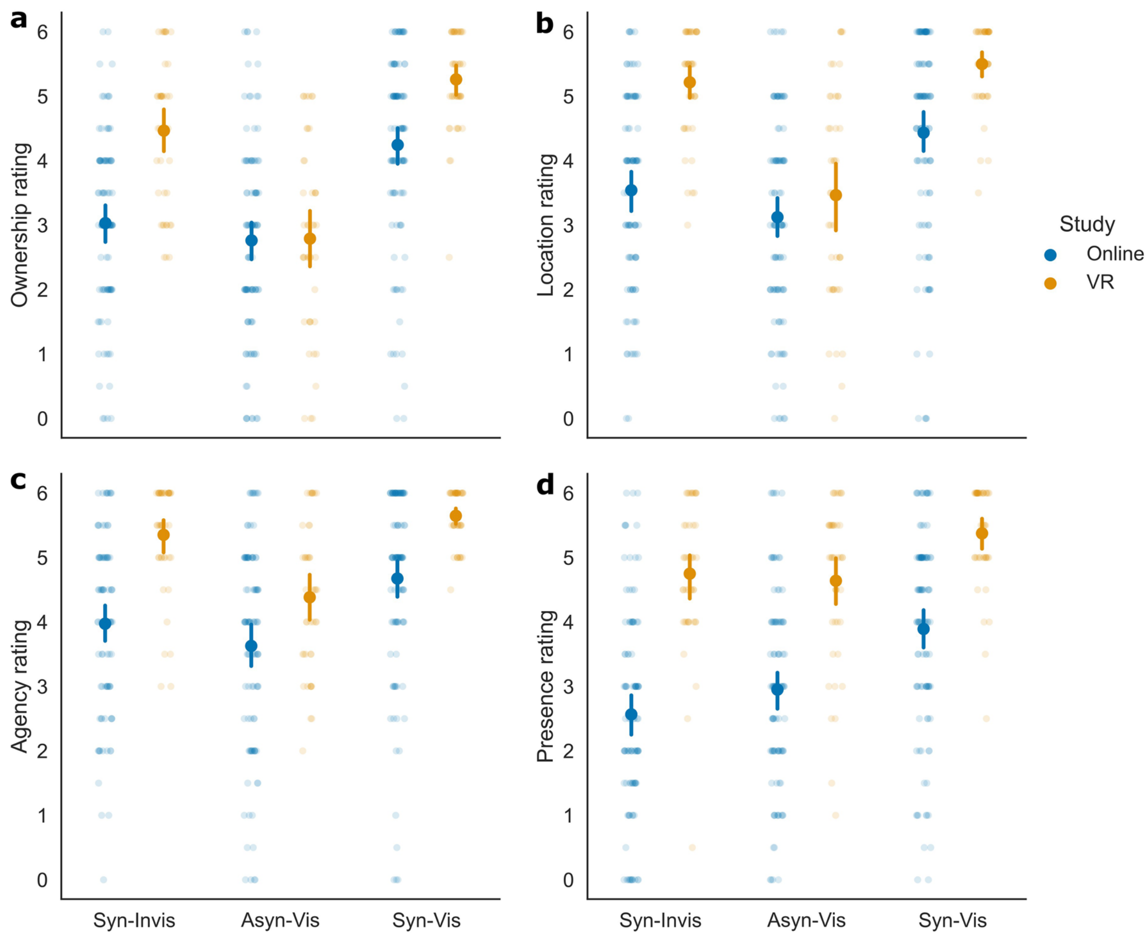

Figure 2. Ratings per condition for the items on (**a**) ownership, (**b**) location, (**c**) agency, and (**d**) presence. Data points are averaged over Threat per participant. Point-plots show mean values. Error bars represent the 95% within-subject CI. Individual dots represent averaged data per participant.

Results

The goal of this study was to investigate the impact of demand characteristics on embodiment and presence. We therefore constructed two versions of the same experiment, an online and a VR version. The first is intended to assess participants' expected experimental outcomes while passively observing a participant in the VR experiment, whereas the second directly measures the outcome while participants actively performed the VR experiment. We examined whether ratings in the online experiment matched those in the VR experiment. This was done by testing if the manipulations similarly influenced participants ratings in the online and VR experiments, which was indicated by model slopes of the same sign. If manipulations had a similar effect in both experiments, this would suggest that participants were aware of the research hypotheses. In addition, we wanted to know whether participants prone to suggestibility were more likely to report sensations of embodiment and presence. In this section, we will describe the results of the comparison between the online and VR experiments ('Demand characteristics: Similar effects in online and VR experiments'), and then present the results on the influence of suggestibility ('Suggestibility: Effects on ownership and location ratings').

Demand characteristics: similar effects in online and VR experiments. Ratings differed between online and VR experiments, with generally higher ratings in the VR experiment for embodiment and presence (Fig. 2). The results further showed an effect of Movement (Asyn-Vis compared to Syn-Vis) in both experiments, and an effect of Visibility (Syn-Invis compared to Syn-Vis) more pronounced in the online experiment. Fear ratings in response to threat were similar between the online and the VR experiment (Fig. 3), however, participants rated the control stimulus as less fearful in the VR, compared to the online experiment. In the following, we will analyse the model slopes representing the differences between the two factor levels, which can be interpreted as the effect the manipulation had on the rating responses.

The slope for Study was significant for ownership, location, agency, and presence, but not for fear (Table 1). In addition, ratings were significantly influenced by Movement and Visibility for all items, and Threat only for the fear item. These effects should not be interpreted without their interactions. We found significant interactions between Study and Movement for the ownership and location items. Additionally, the interaction between Study

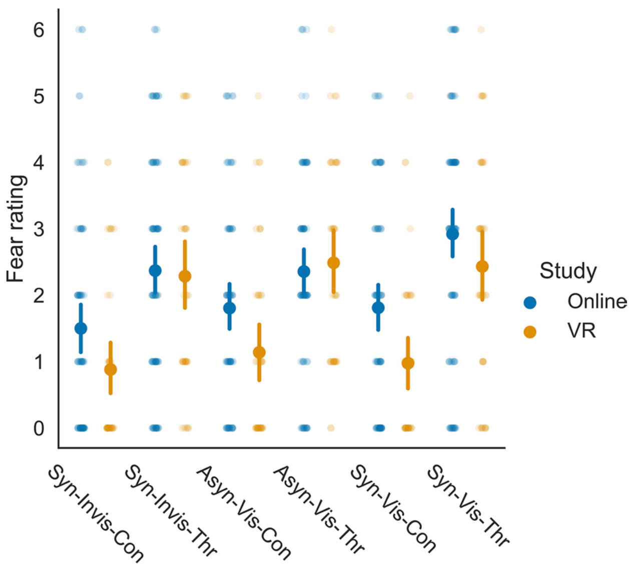

Figure 3. Ratings per condition for the fear item. Point-plots show mean values. Error bars represent the 95% within-subject CI. Individual dots represent ratings per participant.

Item	Predictor	*b*	SE	df	*t*	*p*	CI_{lower}	CI_{upper}
Ownership	Intercept	3.233	0.106	165.844	30.636	< .001	3.025	3.441
	Study	0.788	0.211	165.844	3.735	< .001	0.373	1.205
	Movement	2.025	0.101	620.557	19.990	< .001	1.826	2.224
	Visibility	1.052	0.101	620.461	10.456	< .001	0.854	1.250
	Study:Movement	0.898	0.203	620.557	4.434	< .001	0.501	1.296
	Study:Visibility	− 0.573	0.201	620.461	− 2.845	= .005	− 0.968	− 0.177
Location	Intercept	3.798	0.111	164.439	34.122	< .001	3.579	4.017
	Study	1.091	0.223	164.439	4.900	< .001	0.652	1.530
	Movement	1.695	0.100	618.904	16.932	< .001	1.499	1.892
	Visibility	0.680	0.100	618.953	6.801	< .001	0.483	0.876
	Study:Movement	0.628	0.200	618.904	3.135	= .002	0.235	1.021
	Study:Visibility	− 0.761	0.200	618.953	− 3.806	< .001	− 1.153	− 0.368
Agency	Intercept	4.313	0.107	157.914	40.251	< .001	4.101	4.524
	Study	1.206	0.210	146.530	5.733	< .001	0.791	1.621
	Movement	1.118	0.078	618.799	14.362	< .001	0.965	1.271
	Visibility	0.569	0.081	616.536	7.026	< .001	0.410	0.728
	Study:Visibility	− 0.679	0.145	617.725	− 4.693	< .001	− 0.963	-0.395
Presence	Intercept	3.711	0.113	163.060	32.842	< .001	3.488	3.934
	Study	1.872	0.222	152.093	8.430	< .001	1.434	2.310
	Movement	0.910	0.080	644.293	11.392	< .001	0.753	1.066
	Visibility	1.005	0.082	640.809	12.309	< .001	0.845	1.166
	Study:Visibility	− 0.606	0.145	641.592	− 4.176	< .001	− 0.891	− 0.321
Fear	Intercept	1.809	0.127	161.091	14.194	< .001	1.557	2.060
	Study	− 0.431	0.249	147.769	− 1.726	= .086	− 0.923	0.061
	Movement	0.215	0.089	641.591	2.417	= .016	0.040	0.389
	Visibility	0.343	0.087	639.878	3.962	< .001	0.173	0.513
	Threat	1.176	0.077	642.450	15.208	< .001	1.024	1.328
	Study:Threat	0.441	0.155	642.448	2.851	= .004	0.137	0.745

Table 1. Fixed effects from the LMM. Statistics are reported for each item with slope (*b*), standard error (SE), degrees of freedom (df), *t*-value (*t*), *p*-value (*p*), and the 95% confidence interval (CI_{lower} and CI_{upper}).

Item	Study	Predictor	*b*	SE	df	*t*	*p*	CI_{lower}	CI_{upper}
Ownership	Online	Intercept	2.835	0.126	124.159	22.581	<.001	2.587	3.083
		Movement	1.577	0.113	412.411	13.944	<.001	1.355	1.799
		Visibility	1.349	0.113	413.496	11.910	<.001	1.126	1.571
	VR	Intercept	3.629	0.138	58.412	26.259	<.001	3.353	3.904
		Movement	2.471	0.174	214.460	14.166	<.001	2.127	2.814
		Visibility	0.765	0.173	213.812	4.431	<.001	0.425	1.105
Location	Online	Intercept	3.249	0.136	123.580	23.888	<.001	2.980	3.518
		Movement	1.383	0.117	412.353	11.855	<.001	1.154	1.612
		Visibility	1.069	0.117	413.022	9.137	<.001	0.838	1.298
	VR	Intercept	4.348	0.122	60.175	35.577	<.001	4.104	4.591
		Movement	2.005	0.160	213.270	12.559	<.001	1.691	2.320
		Visibility	0.292	0.159	212.943	1.836	=.068	−0.021	0.605
Agency	Online	Intercept	3.724	0.133	119.277	27.922	<.001	3.460	3.987
		Movement	1.060	0.098	409.110	10.792	<.001	0.867	1.252
		Visibility	0.887	0.099	410.118	8.964	<.001	0.692	1.081
	VR	Intercept	4.887	0.098	59.881	50.008	<.001	4.692	5.081
		Movement	1.236	0.126	213.725	9.840	<.001	0.989	1.483
		Visibility	0.283	0.124	213.092	2.274	=.024	0.038	0.527
Presence	Online	Intercept	2.753	0.133	122.235	20.635	<.001	2.490	3.017
		Movement	0.991	0.105	430.823	9.456	<.001	0.785	1.197
		Visibility	1.345	0.101	429.103	13.319	<.001	1.147	1.544
	VR	Intercept	4.689	0.143	49.422	32.830	<.001	4.403	4.974
		Movement	0.748	0.115	214.616	6.489	<.001	0.521	0.974
		Visibility	0.623	0.114	214.339	5.463	<.001	0.398	0.847
Fear	Online	Intercept	1.979	0.146	119.136	13.567	<.001	1.691	2.267
		Movement	0.366	0.109	431.518	3.375	=.001	0.153	0.579
		Visibility	0.437	0.105	430.059	4.185	<.001	0.232	0.643
		Threat	0.959	0.090	438.077	10.659	<.001	0.782	1.135
	VR	Intercept	1.681	0.184	49.783	9.117	<.001	1.312	2.049
		Movement	−0.092	0.152	210.771	−0.606	=.545	−0.391	0.207
		Visibility	0.137	0.152	210.510	0.905	=.366	−0.161	0.436
		Threat	1.402	0.124	210.397	11.297	<.001	1.157	1.646

Table 2. Fixed effects from follow-up models for Study. Statistics are reported for each item and Study condition with slope (*b*), standard error (SE), degrees of freedom (df), *t*-value (*t*), *p*-value (*p*), and the 95% confidence interval (CI_{lower} and CI_{upper}).

and Visibility was significant for all items, except for the fear item, where no such interaction was included in the model. For the fear item, there was a significant interaction between Study and Threat.

Follow-up models were constructed to better understand the interaction effects. Per item, we constructed an LMM for Study, including Movement and Visibility as predictors for all items, and in addition, Threat for the fear item. All model components were significant, except in the VR group, where Movement (fear item) and Visibility (location and fear item) were not significant (Table 2). Positive slopes in both the online and VR experiments suggest that manipulations influencing participants' ratings in the online experiment also influenced their ratings in the VR experiment. Indeed, all significant slopes were positive, indicating that participants rated the items as higher when the avatar was visible (compared to invisible), the movements were synchronous (compared to asynchronous), or a threat (compared to control) stimulus appeared (see Figs. 4 and 5). This shows that participants' expectations when rating the online material are in line with participants' responses in the actual VR experiment, suggesting that participants were aware of the research hypotheses.

The follow-up models showed that all significant slopes were positive, which indicates that differences in the magnitude of the effects, as reflected in the steepness of the slopes, drive the significant interactions involving Study in the overall models. To assess whether the manipulations led to a higher increase in the ratings in the online or VR experiment, we compared the intercepts and slopes between the respective LMMs with a *Z*-test. Differences in slopes indicate that our manipulations had a more pronounced effect in either the online or VR experiment. The intercepts differed significantly between online and VR experiments for all comparisons, except for the fear item (ownership: $Z = 4.252$, $p < 0.001$; location: $Z = 6.008$, $p < 0.001$; agency: $Z = 7.034$, $p < 0.001$; presence: $Z = 9.903$, $p < 0.001$; fear: $Z = -1.268$, $p = 0.205$). For Movement, the increase in ownership and location ratings was significantly higher in the VR experiment (ownership: $Z = 4.299$, $p < 0.001$; location: $Z = 3.145$, $p = 0.002$). This suggests that Movement had a stronger effect on ownership and location ratings in the VR than the online

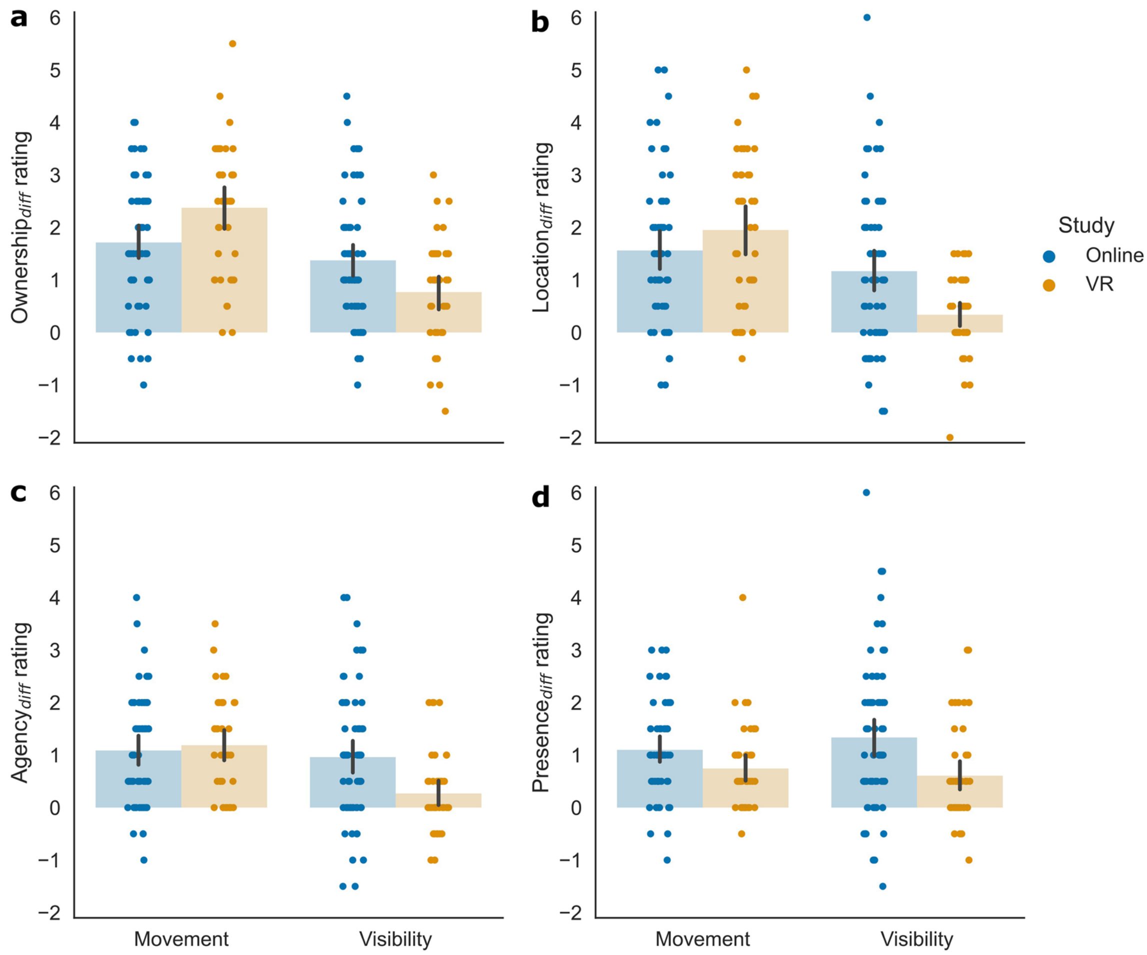

Figure 4. Averaged rating differences for the Movement and Visibility manipulations for the items on (**a**) ownership, (**b**) location, (**c**) agency, and (**d**) presence. Data points are averaged over Threat per participant. Values represent differences between factor levels of Movement (synchronous, asynchronous) and Visibility (visible, invisible). Positive values indicate higher ratings in synchronous and visible conditions. Bar-plots show mean values and do not represent exact model slopes. Error bars represent the 95% within-subject CI. Individual dots represent difference values per participant.

experiment. For Visibility, ratings for the different items (ownership, location, agency, and presence) showed a significantly stronger increase in the online experiment (ownership: $Z = -2.828$, $p = 0.005$; location: $Z = -3.932$, $p < 0.001$; agency: $Z = -3.804$, $p < 0.001$; presence: $Z = -4.744$, $p < 0.001$). This suggests that Visibility increased the ratings in the online experiment more than in the VR experiment. For the subjective location ratings, we already observed that Visibility only influenced ratings in the online experiment, but not in the VR experiment (see Table 2). Additionally, Threat showed a significantly stronger increase in the fear rating in the VR experiment ($Z = 2.892$, $p = 0.004$). This effect is likely based on differences between ratings in the control condition of the online and VR experiments (see Fig. 3), with lower subjective fear ratings in the VR group, when a control stimulus was presented. Despite this, the fear ratings in the online and VR experiments were highly similar. For Movement, the increase in the fear ratings was higher in the online experiment ($Z = -2.454$, $p = 0.014$), reflecting that Movement had an effect in the online, but not in the VR experiment (see Table 2). However, as no interaction between Study and Movement was present in the overall model (see Table 1), this result should be interpreted with caution. All other comparisons of slopes between the online and the VR experiment (Movement for the agency and the presence item; Visibility for the fear item) were not significant ($p \geq 0.103$), as could be expected from the missing interactions in the overall model. Altogether, we observed differences between slopes of the online and VR experiments. Movement had a stronger effect on embodiment (except agency) ratings in the VR experiment, whereas Visibility had a stronger effect on embodiment and presence ratings in the online experiment. Most importantly, the slopes in both experiments had the same sign, indicating that the manipulations had a similar effect on participants' ratings in the online and VR experiments. This suggests that demand characteristics affected our results on embodiment and presence.

Suggestibility: Effects on ownership and location ratings. Our results from the online experiment show that participants can accurately rate which manipulations influence embodiment and presence, and might

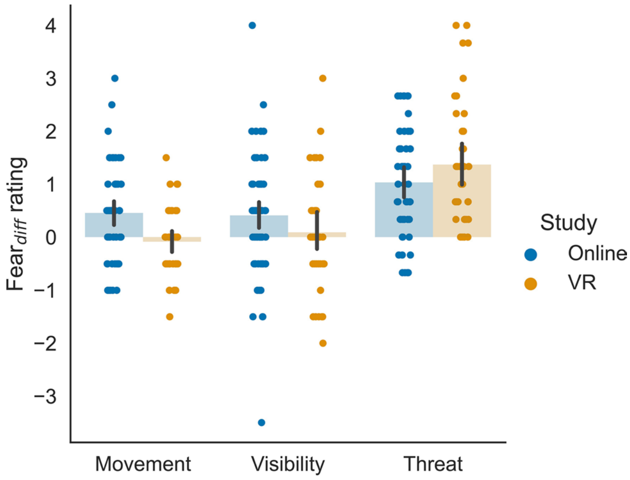

Figure 5. Averaged difference between Movement, Visibility and Threat manipulations for the fear item. Data points are averaged over Threat per participant for Movement and Visibility. For Threat, data points are averaged over the Visibility and Movement manipulations. Values represent differences between factor levels of Movement (synchronous, asynchronous), Visibility (visible, invisible), and Threat (threat, control). Positive values indicate higher ratings in synchronous, visible, and threat conditions. Bar-plots show mean values and do not represent exact model slopes. Error bars represent the 95% within-subject CI. Individual dots represent difference values per participant.

therefore know the underlying hypotheses. Participants prone to suggestibility might more strongly change their experiences in accordance to the perceived demand characteristics of the experiment [c.f.,[8,9]]. To uncover the role of suggestibility, we reanalysed the models for each experiment and included Suggestibility as an additional predictor. Two-way interactions between Suggestibility and the other model components were considered as predictors as well. For the VR experiment, some predictors had no influence on the rating (Visibility for the location and fear item, Movement for the fear item, see Table 2), and were therefore removed from the model before adding Suggestibility as a new predictor. An ANOVA was used to compare models with different predictors.

Suggestibility (ownership: $b = 0.736$ [0.220, 1.253], SE = 0.258, $t(47.773) = 2.848$, $p = 0.006$; location: $b = 0.619$ [0.160, 1.080], $t(47.893) = 2.692$, $p = 0.010$) as well as the interaction between Suggestibility and Movement (ownership: $b = -0.625$ [−1.237, −0.013], SE = 0.311, $t(214.305) = -2.011$, $p = 0.046$; location: $b = -0.929$ [−1.487, −0.370], SE = 0.284, $t(213.411) = -3.271$, $p = 0.001$) were significant predictors for the ownership and the location ratings in the VR experiment. All other included predictors remained significant ($p < 0.001$, see supplementary materials E). A follow-up model on the interaction showed that ratings on ownership and location increased with participants' suggestibility in the asynchronous movement condition (ownership: $b = 1.025$ [0.143, 1.906], SE = 0.440, $t(42.998) = 2.329$, $p = 0.025$; location: $b = 1.057$ [0.071, 2.042], SE = 0.491, $t(42.320) = 2.151$, $p = 0.037$), but not in the synchronous movement condition (ownership: $b = 0.410$ [−0.082, 0.900], SE = 0.245, $t(43.749) = 1.674$, $p = 0.101$; location: $b = 0.155$ [−0.189, 0.501], SE = 0.172, $t(44.135) = 0.900$, $p = 0.373$). Figure 6 illustrates the relationship between Suggestibility and the subjective ratings indicating that participants with higher scores in the SSS also gave higher ratings when answering items on ownership and location in the asynchronous movement condition.

Discussion

We investigated the impact of demand characteristics by comparing participants' ratings from experiments in which they rated the questionnaire items by only watching a participant performing the experiment to ratings in the actual experiment. In line with previous findings [e.g.,[8]], we showed that participants' expectations about the experimental outcomes on embodiment and presence mirror the corresponding research hypotheses. This shows that demand characteristics do not only influence results in RHI experiments but could also affect embodiment measures in this sensorimotor VR task. This finding was not restricted to embodiment, but was also found for presence. When comparing the results of the online and VR experiments, we observed differences in the magnitude of the effects. Movement had a stronger influence on embodiment (except agency) in the VR experiment, whereas Visibility had a stronger effect on embodiment and presence in the online experiment. The effect of Threat on the fear ratings was also more pronounced in the VR experiment. In addition, suggestibility predicted subjective ratings on ownership and location in the asynchronous movement condition suggesting that the relationship between suggestibility and embodiment ratings differed depending on the Movement manipulation.

The effect of demand characteristics.

We applied different experimental manipulations to investigate to which extent embodiment and presence are affected by demand characteristics. The key finding of our study was that participants were able to judge the influence of the different manipulations on the questionnaire ratings in the online version of the experiment. This was true for all three manipulations: Movement, Visibility, and

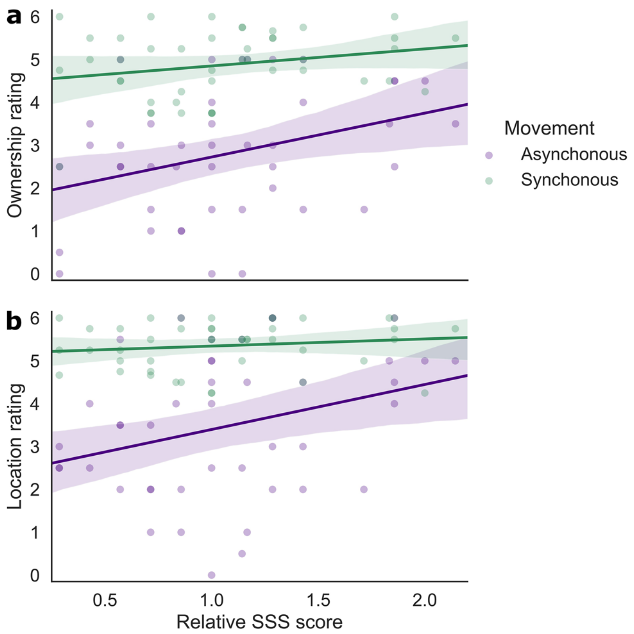

Figure 6. Suggestibility and Movement in the VR experiment for items on (**a**) ownership and (**b**) location. For each participant, data points are averaged over Visibility and Threat, per Movement condition. The regression plot is based on the data and does not represent the exact model slopes. Shaded areas represent the 95% within-subject CI. Individual dots represent averaged data per participant.

Threat. These results indicate that participants in the online experiment were aware of the research hypotheses and that participants in the VR experiment might have gained the same knowledge.

In the VR experiment, we observed an effect of Movement on embodiment, with higher ratings in the synchronous movement condition. This is in line with previous results showing that visuomotor[36] and visuotactile[36,37] synchrony can induce embodiment. In addition, we observed an effect of Movement on presence, supporting the finding that performing body movements in VR is positively related to presence[38]. We also found an effect of avatar Visibility on embodiment (ownership and agency), with higher ratings when the avatar was visible, supporting previous results[39]. Nevertheless, it has been shown that participants can also perceive embodiment of an invisible body[40]. An effect of Visibility was also observed for presence, with higher ratings when the avatar is visible. This is in line with findings that having a virtual body representation promotes presence [c.f.,[23,41]]. Contrary to a previous study[42], the fear ratings in the VR experiment seemed to be only influenced by Threat and not by our other manipulations.

Importantly, the effects of Movement, Visibility, and Threat were also present in the online experiment. This finding is in line with previous studies claiming that embodiment measures might be confounded by demand characteristics, i.e. the knowledge about the research hypotheses[8,13,14]. We extended these results to presence where we observed similar effects. These results highlight the importance to consider demand characteristics when investigating embodiment and presence.

We also observed differences in the magnitude of the effects, with Movement having a generally more pronounced effect on embodiment ratings in the VR experiment, and Visibility on embodiment and presence ratings in the online experiment. We do not believe that mere context effects, i.e. rating questionnaire items online in a private atmosphere compared to a laboratory setting where an experimenter is present, strongly influenced the results. This is supported by a previous study showing that a behavioural task in a laboratory and an online experiment yielded similar results[43]. However, rating questionnaire items online or in VR might involve different perceptual and decision-making processes. The response modalities differ in so far that participants either reported their experienced sensations in the VR experiment or their expected sensations in the online experiment. Overall, these differences in magnitude stand against the clear similarities of both experiments indicating that demand characteristics cannot be ruled out when interpreting results on embodiment and presence. This does not mean that results on embodiment and presence are necessarily based on demand characteristics. Participants could recognise the experiment's hypotheses, but still genuinely experience embodiment and presence.

The results reported here could be limited by the fact that some participants might have perceived the control stimulus as abyss, especially when presented with this stimulus first. There could therefore be a tendency to rate the control stimulus higher, if it was presented before the threat stimulus. This is unlikely in the online experiment as we used a catch item to exclude participants who could not discriminate between the control and threat stimuli. For the VR experiment, we observed similar fear ratings for presenting the control stimulus before or after the first threat stimulus, which also speaks against such a bias.

The effect of suggestibility. Guessing the research hypotheses could affect the results, e.g. by a response bias or by participants' suggestibility. We measured participants' suggestibility and observed an effect on ownership and location ratings for asynchronous movements in the VR experiment. We did not find this effect in our online experiment, possibly due to different requirements of the experiment. Participants rated their experienced sensations in the VR experiment, whereas they rated their expected sensations in the online experiment. It is conceivable that suggestibility, as the ability to change ones experiences to match perceived demands[9,17], is less likely to affect the more cognitive tasks as applied in the online experiment.

Previous findings showed an effect of suggestibility on ownership under synchronous stroking of the rubber hand[18]. Although, we used a different experimental design, we would have expected similar results, especially as we used the same measure of suggestibility. The lack of an influence of suggestibility on subjective ratings in the synchronous movement condition is likely caused by a ceiling effect. This suggests that questionnaire items in both conditions can be confounded by suggestibility, which is in line with findings reporting an effect of suggestibility for synchronous and asynchronous stimulations[9,44].

Comparing illusion and control conditions, e.g. synchronous and asynchronous conditions, could control for suggestibility. Ehrsson et al.[20] used this approach when reanalysing data by Lush et al.[9] and found no relation between suggestibility and subjective ratings on the RHI. In our study, suggestibility predicted subjective ratings on ownership and location only in the asynchronous movement condition. In this case, investigating differences between both conditions cannot control for suggestibility. To identify conditions which are differently influenced by suggestibility, small exercises measuring individual suggestibility should be applied [c.f.,[18,30–32]].

Our results on suggestibility are limited by the fact that some faint noise from a server room was audible while participants performed the SSS in the VR experiment. This noise might have interfered with acoustic tasks in the SSS making it difficult to detect an influence from suggestibility on participants' ratings. We nevertheless found such an influence for ownership and location. In addition, the SSS scores did not differ between the online and the VR experiment, making it unlikely that the noise from the server room biased our results.

We only used a subset of SSS exercises. If psychometric properties of this subset are different from the overall properties is difficult to evaluate because the study on which we based our version of the SSS did not report psychometric properties. The PCS[31] reports psychometric properties and could be an alternative for future experiments. It was not officially published when we created this study.

As randomisation of experimental blocks was not possible in the online experiment, we always presented the SSS in the beginning. The online and the VR experiment should closely resemble each other, which is why we decided to also present the SSS in the VR experiment first. In theory, this could have led to carry over effects, which, however, would be consistent across experiments.

Challenges in embodiment and presence research. Demand characteristics challenge research on embodiment and presence. Here, we show that participants' ratings in the online experiment are in line with the reported sensations of participants in the actual VR experiment. This indicates that demand characteristics could have confounded the ratings on embodiment and presence. Participants' ratings could reflect their knowledge about the experiment rather than reports of embodiment and presence sensations per se. This could express itself in a response bias, e.g. when participants actively try to produce responses confirming the hypotheses[10], or might provide the demands against which suggestible participants can match their experiences [e.g.,[9]].

Demand characteristics are not the only factor reducing the validity of subjective measures. Questionnaire items are also the only way participants can express themselves, and sensations reported could in theory be a consequence of surveying participants[45]. To reach conclusive results on embodiment and presence, we therefore need to consider additional methodological factors concerning standardisations of experimental designs [c.f.,[46,47]], concise and measurable definitions of constructs, and the use of objective measures.

Finding suitable objective measures for embodiment and presence turns out to be a challenge. First, demand characteristics might also confound objective measures such as proprioceptive drift and skin conductance[13]. For example, if participants' experiences change according to demand characteristics[9,12], this might lead to a change in their physiological response[48]. It is therefore questionable how effective these measures are in preventing the confounding effect of demand characteristics. Second, results from physiological measures are not consistently reported to match self-reports of embodiment [c.f.,[49]] and presence [c.f.,[24]]. Accordingly, we found that the skin conductance response to threat was unaffected by manipulations affecting embodiment and presence ratings. This might suggest that physiological and subjective measures might rely on different processes. This view is supported by recent findings which show that objective and subjective measures on ownership and agency might partly rely on different information[50]. It is therefore difficult to indicate which measures are best suited to study embodiment and presence.

Apart from these challenges, ratings on embodiment and presence are more or less influenced by the same manipulations. This makes it difficult to separate the two constructs experimentally, and it is unclear, to which extent participants are able to differentiate their reported sensations when rating questionnaire items. These findings support current ideas suggesting that embodiment and presence could be explained within a common framework[51,52].

Conclusion. In this study, we directly compared embodiment and presence ratings from a VR study and its online version. We showed that participants' ratings in the online experiment were similar to the responses in the VR experiment indicating that participants were aware of the research hypotheses. This replicates previous findings on demand characteristics for embodiment, and extends these to presence. It remains an open question how exactly participants' knowledge influences subjective and objective measures on embodiment and presence.

Future research is challenged to find methods eliminating the confounding effects of demand characteristics, e.g. by finding and applying effective control procedures.

Data availability

The videos of the different conditions as well as data created during the analysis of this study are available at: https://osf.io/3m4y8/.

Received: 13 April 2022; Accepted: 5 August 2022
Published online: 18 August 2022

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Acknowledgements

We would like to thank Yanina Tena Garcia, Munyke Kerllyn Stelter and Nikola Krystyna Zalomska for collecting data. We also thank Greta Saiz for creating a first draft of the virtual laboratory used in this study. This work was supported by the German Research Foundation, International Research Training Group, IRTG 1901, "The Brain in Action" and by "The Adaptive Mind", funded by the Excellence Program of the Hessian Ministry for Higher Education, Research, Science and the Arts.

Author contributions

P.P.F., and H.K. designed the experiment. P.P.F. analysed the data and created the figures. P.P.F., H.K., and K.F., interpreted the data. P.P.F., drafted the manuscript, and H.K., and K.F., made critical revisions. H.K., supervised the project.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-022-18160-5.

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3 Study III: Egocentric cues influence the allocentric spatial memory of object configurations for memory-guided actions

Forster, Fiehler, & Karimpur, 2023, *Journal of Neurophysiology*, in press[1]

[1]https://doi.org/10.1152/jn.00149.2023

Egocentric cues influence the allocentric spatial memory of object configurations for memory-guided actions

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Egocentric cues influence allocentric spatial memory

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Abstract

Allocentric and egocentric reference frames are used to code the spatial position of action targets in reference to objects in the environment, i.e., relative to landmarks (allocentric), or the observer (egocentric). Previous research investigated reference frames in isolation, for example, by shifting landmarks relative to the target and asking participants to reach to the remembered target location. Systematic reaching errors were found in the direction of the landmark shift and used as a proxy for allocentric spatial coding. Here, we examined the interaction of both allocentric and egocentric reference frames by shifting the landmarks *as well as* the observer. We asked participants to encode a 3D configuration of balls, and to reproduce this configuration from memory after a short delay followed by a landmark or an observer shift. We also manipulated the number of landmarks to test its effect on the use of allocentric and egocentric reference frames. We found that participants were less accurate when reproducing the configuration of balls after an observer shift, which was reflected in larger configurational errors. In addition, an increase in the number of landmarks led to a stronger reliance on allocentric cues and a weaker contribution of egocentric cues. In sum, our results highlight the important role of egocentric cues for allocentric spatial coding in the context of memory-guided actions.

Key words: reference frames, spatial coding, spatial representations, visual working memory, virtual reality

New & Noteworthy

Objects in our environment are coded relative to each other (allocentrically) and are thought to serve as independent and reliable cues (landmarks) in the context of unreliable egocentric signals. Contrary to this assumption, we demonstrate that egocentric cues alter the allocentric spatial memory, which could reflect recently discovered interactions between allocentric and egocentric neural processing pathways. Further, additional landmarks lead to a higher contribution of allocentric and a lower contribution of egocentric cues.

Introduction

Different classes of spatial reference frames are used for interacting with objects (1). For example, when we grab a cup of tea, the cup can be represented relative to the observer, i.e., in an egocentric reference frame. Visually-guided actions primarily rely on an egocentric, gaze-centered, reference frame in which the action target is represented with respect to the current position of gaze (2). As a consequence, continuous spatial updating of the target representation is required to compensate for changes in the spatial origin with an observer's movement (3).

The cup can also be represented with respect to other objects in the environment, such as the tea pot, i.e., in an allocentric reference frame. Relying on multiple landmarks can improve allocentric spatial coding by providing a more stable point of origin compared to a single landmark (4). As allocentric cues are independent of the observer's movement, they are more persistent over time (5) and therefore especially suitable for memory-guided movements (6; 7).

The so called "object-shift paradigm" is a prominent task to investigate the contribution of allocentric reference frames for memory-guided actions. In this paradigm, participants are asked to reach to the remembered location of a target object while surrounding objects (landmarks) are shifted (7–9). Relying on the change blindness effect (10) ensures that those small landmark shifts remain unnoticeable to participants. The results show that reach endpoints in the object-shift paradigm systematically deviate in the direction of the landmark shift, reflecting the use of allocentric reference frames for memory-guided actions (7; 8). These deviations are larger if more landmarks are shifted (4; 8). Nevertheless, deviations in reach endpoints are usually only halfway the actual landmark shift, even if all available landmarks are shifted in the same direction (4; 7; 8). This suggests an additional contribution of egocentric reference frames that has never been tested in the object-shift paradigm.

Previous research shows that action targets are concurrently represented in multiple spatial reference frames (11). When allocentric and egocentric cues are available, they seem to be integrated by additionally considering the stability of the allocentric cues (9; 12). However, these studies leave open whether and how allocentric and egocentric cues interact and impact each other. The extent to which neural pathways for allocentric and egocentric reference frames are intertwined (11), gives reason to believe that allocentric configurations could be altered by egocentric signals leading to behavioral changes.

In this study, we investigated the interaction of allocentric and egocentric reference frames in an adapted version of the object-shift paradigm. Choosing this design ensures comparability to previous studies (e.g., 8; 9; 13) and expands it to effects of egocentric cues. We shifted the landmarks (allocentric cues) *and* the observer (egocentric cues) and varied the number of available landmarks to test its influences on allocentric and egocentric coding. Participants were asked to reproduce the spatial configuration of balls presented in an encoding scene by placing one to five virtual balls (target objects) at the remembered positions in a virtual environment after a memory delay and the respective shift. We analyzed participants' placement error relative to the maximum expected error due to the landmark (allocentric weight) or observer shift (egocentric weight). Moreover, we analyzed how well participants reproduced the configuration of balls by comparing the reproduced and the originally presented configuration of balls (configurational error).

We would expect that placement errors should increase after landmark and observer shifts, if participants rely on allocentric and egocentric cues, respectively. Since allocentric cues are ultimately converted into egocentric coordinates to create a motor plan that allows for interaction with objects (11), manipulating egocentric cues should influence the memory of allocentric object relations. Shifting the observer should consequently decrease allocentric weights and increase configurational errors. Further, if the number of landmarks influences the relative contribution of allocentric and egocentric cues, allocentric weights should decrease and egocentric weights increase the fewer landmarks are available. Likewise, configurational errors should increase when fewer landmarks are available.

Methods

Participants

Participants were recruited via university e-mail and received either monetary compensation or course credits for their participation. We screened participants for normal stereo vision with the Stereo Fly Test (Stereo Optical Co., Inc., Chicago, USA) and right handedness with the Edinburgh Handedness Inventory (EHI, 14). We excluded six participants in total. Three participants failed the criterion for stereo vision (values of ≥6 required) and another three participants showed average lateral ball placement errors that exceeded the sum of the median error and the median absolute deviation (MAD). Median error and *MAD* were calculated for the ball placement errors across all participants and conditions. We decided for these criteria a priori since extreme outliers could introduce skewness, distort representational accuracy, and potentially violate the assumptions of subsequent analyses. This protocol was created after a careful consideration of their potential impact on the overall integrity and interpretability of the study's results. The final sample consisted of 35 participants (24 female, 11 male) with a mean age of 23.14 (*SD* = 3.50) years. The experiment was approved by the local ethics committee, and is in line with the Declaration of Helsinki (2013, except §35, pre-registration). All participants provided written informed consent.

Setup and Stimuli

This experiment was performed using virtual reality (VR) technology, displayed via a Vive Pro Eye (HTC Corporation, Taoyuan City, Taiwan) head mounted display (HMD, 90Hz frame rate, 1440x1600 pixels per eye, 110° field of view) together with a Vive controller. By presenting slightly different images to each eye (emulating disparity) and tracking head movements, participants perceive a three-dimensional virtual environment which updates with their head movements. To calculate the position of the HMD (respectively the participant's head position) in space, sensors on the controller and HMD are used to detect infrared light from the lighthouses. The HTC Vive is a commonly used device that allows scientists to immerse participants in a virtual environment and to study their behavior (15–17).

The experiment was run in Unity (Unity Technologies, San Francisco, CA, USA). We simulated the observer shift by a lateral movement of the observer's camera position in the virtual environment. The virtual environment consisted of a pebbly underground and a structured blue-grey wall. Using structured instead of uniform materials is essential to create an optic flow pattern during the observer shift (18).

The configuration of balls consisted of six white balls that could be encoded either individually or as chunks (19), thereby reducing task difficulty likely below the upper limit of visual working memory capacity (20). Staying within the boundaries of visual working memory capacity is also beneficial because dual-task interference in visual working memory is mostly happening during maintenance of information and when memory capacities are exceeded (21). To control for any additional interference effects of visual working memory, we kept memory demands in both landmark and observer shift conditions comparable.

The balls had a size of 5 cm in radius and a distance of at least 17 cm to each other. Participants stood approximately 55 cm away from this configuration. The starting position was marked on the virtual floor and a tone was played when participants came too close to the configuration of balls. We used three different configurations, one for each number of landmarks (see Design), to refrain participants from learning the balls' positions.

Design

To probe allocentric and egocentric coding we introduced a lateral shift of the observer (*observer shift*) or the landmarks (*landmark shift*). The size of the landmark shift (4 cm) was determined in a pilot study so that it was small enough to be unnoticeable to participants (confirmed by verbal reports after the experiment) and large enough to produce systematic placement errors in the direction of the landmark shift, in line with previous studies (c.f., 4; 9). This allowed us to examine the use of allocentric cues in the different experimental conditions. To investigate the use of egocentric cues, we simulated a lateral shift of the participant (20 cm) by moving the observer's camera position in the virtual environment. This guaranteed egocentric shifts comparable within and between participants. To add more variability and to minimize the potential risk that participants subconsciously adjust for a constant shift, we added a lateral shift of ±0.5 cm to both the landmark and the observer shift. In the baseline condition, neither a shift of the observer nor the landmark(s) occurred.

We further manipulated the number of *landmarks* by presenting either one, three or five landmarks. This resulted in a 3x3x3 within-subject design with the factors landmark shift (left, none, right), observer shift (left, none, right), and number of landmarks (one, three, five). We tested all 27 combinations and repeated each combination in two separate blocks (54 trials in total). The order of trials in each block was randomized.

Procedure

Participants first performed the stereo vision and handedness tests. For the experiment, we instructed participants to memorize a configuration of balls and told them that a subset of those balls would later reappear at the same position. It would then be their task to place the missing balls, i.e., the target objects, back to the memorized position. Each trial started with the presentation of an encoding scene (5000 ms) which consisted of a configuration of six balls (Figure 1). Then, the six balls were replaced by a mask (200 ms) to prevent visual after-effects. The mask was followed by a short delay (1800 ms) showing the encoding scene without the balls. In the test scene (1000 ms), one, three, or five of the balls from the encoding scene, now functioning as landmarks, briefly reappeared. Unnoticeable to participants, the presentation of these landmarks could be laterally shifted by 4 cm (left or right) compared to the position in the encoding scene. In trials without landmark shift, the landmarks were presented at the same position as in the encoding scene. After the presentation of the test scene, the landmarks were removed from the scene and a lateral observer shift of 20 cm (left or right) was induced by a lateral movement of the observer's camera position for 1000 ms. Following the landmark and/or observer shift(s), participants had the task to reproduce the ball configuration seen in the encoding scene from memory. To do so, they used the controller to successively place the target objects (one, three, or five) back to the positions observed in the encoding scene. In trials without observer shift, participants placed the target objects directly after the presentation of the test scene. No landmarks were present during the ball placement. None of the participants reported to have noticed a landmark shift in a post-experiment inquiry.

-- Insert Figure 1 about here --

Pre-processing and analysis

We used Python 3.8 to pre-process the data. To compare the contribution of each reference frame, we calculated *allocentric* and *egocentric weights.* We introduced a baseline correction to take individual biases into account when placing remembered target objects. For the allocentric weights, we subtracted the baseline condition, i.e., a condition in which neither a landmark nor an observer shift occurred, from conditions with landmark shifts and averaged all placement errors within one trial. To further account for landmark shifts towards the left and the right we calculated the difference between baseline-corrected placement errors after landmark shifts to the left and the right (e.g., -4 cm, for an error of -2 cm to the left and 2 cm to the right). Similarly, we calculated the difference between the maximally expected lateral placement error for shifts towards the left and right (e.g., -8 cm, when landmarks were shifted -4 cm to the left and 4 cm to the right). We then calculated the allocentric weights by dividing the baseline-corrected placement error by the maximally expected lateral placement error (resulting in an allocentric weight of 0.5 in our example). An allocentric weight of 0 indicates that participants did not make use of allocentric cues for the ball placement, whereby an allocentric weight of 1 indicates that they fully relied on this cue. The calculation for the egocentric weights was analogous with the only difference that the weights were calculated with respect to the observer shift (i.e., a simulated shift of 20 cm). By calculating allocentric and egocentric weights we can compare their relative contribution independent of the shift amplitude.

Allocentric and egocentric weights are global measures of influence because they are based on average lateral errors. Nonetheless, shifts could also influence how objects are placed relative to each other (local measures). For example, participants could have memorized specific spatial configurations (e.g., three objects forming a triangle in space). To measure the error that resulted from placing targets in a different spatial configuration (e.g., three objects placed next to each other forming a horizontal line in space), we introduced the *configurational error* as an additional measure. To this end, we used Python's scipy package (version 1.5.2) to perform a Procrustes analysis (22; 23). This is a method used to compare and quantify the error between two or more sets of points in multidimensional space, accounting for differences due to translation, rotation, and scaling (Figure 2). This is necessary to compare errors across different trials and participants. The input matrices are centered around zero and further standardized such that $tr(MM^T) = 1$, where M represents a matrix consisting of object positions. We used the root-mean-squared-error (RMSE) of the spatial disparity between the original and the (transformed) reproduced configuration as a measure of spatial configurational error ($\sqrt{\frac{\sum(M_1 - M_2)^2}{n}}$, where M_1 and M_2 denote the original and the (transformed) reproduced position matrices, respectively, and n denotes the number of target objects). From a methodological point of view, this measure is based on the Procrustes distance (24), taking the number of target objects into account. An error of 0 indicates that the original and the (transformed) reproduced configurations are identical, and higher positive values indicate an increasingly worse spatial overlap. As a configuration must consist of at least two placed target objects, we calculated the configurational error only for trials with one or three landmarks presented in the test scene.

-- Insert Figure *2* about here --

For every number of landmarks, we excluded values outside 1.5 times the interquartile range for the allocentric weights (6.03%), egocentric weights (4.29%) and configurational error (0.24%). Consistent with previous studies (e.g., 4; 13), allocentric and egocentric weights were baseline corrected and calculated across shift directions, resulting in a direction agnostic measure. Keeping with the direction independent allocentric and egocentric weights, we binarized landmark and observer shift variables.

For the data analysis, we used R 4.1.0 to run a linear mixed model (LMM) using the lmerTest package (version 3.1-3). Unlike an ANOVA, LMMs are known to handle well incomplete data sets (for a primer on LMMs see 25). To account for the within-subject design we added a random intercept per participant to the model (see Supplemental Table S1). We used dummy coding as a coding scheme and Restricted Maximum Likelihood (REML) to fit the models. Model selection was based on the Akaike information criterion (AIC). We first report results from the omnibus tests on the models and then specify our results by reporting post-hoc tests based on the estimated marginal means from the emmeans package (version 1.7.4-1) with Holm correction applied. These tests are reported together with the difference between group means (*estimate*) and the standard error (*SE*). Degrees of freedom are calculated based on the Satterthwaite method.

Results

To investigate the interaction of allocentric and egocentric reference frames, we simultaneously or separately manipulated allocentric and egocentric cues and measured the effect on participants' ball placement behavior when reproducing the balls' configuration from memory. Figure 3 shows the descriptive results of the baseline-corrected placement errors in lateral and vertical directions. Landmark and observer shifts clearly introduced placement errors in the lateral direction.

-- Insert Figure 3 about here --

Allocentric weights

The model comparison indicated that a model with a random intercept for participants, and number of landmarks (one, three, five), observer shift (yes, no) and the respective interaction as fixed effects fitted the data best. The allocentric weights (Figure 4a) differed depending on the number of landmarks in the test scene ($F(2, 552.893)=5.369$, $p=.005$, $\eta^2=.018$). The effect of observer shift was non-significant ($F(1, 553.010)=0.043$, $p=.835$, $\eta^2=.000$), but the interaction between the number of landmarks and the observer shift was significant ($F(2, 552.582)=3.483$, $p=.031$, $\eta^2=.012$). Post-hoc tests showed that when no observer shift occurred, allocentric weights were lower when one compared to all five landmarks were presented ($estimate_{1\text{-}5}=-0.333$, $SE=0.129$, $t(552.022)=-2.590$, $p=.049$). The other comparisons for no observer shift were non-significant (three vs five landmarks: $estimate_{3\text{-}5}=-0.064$, $SE=0.129$, $t(552.259)=-0.496$, $p=.620$; one vs three landmarks: $estimate_{1\text{-}3}=-0.269$, $SE=0.128$, $t(551.766)=-2.100$, $p=.145$). When an observer shift occurred, allocentric weights were lower when three compared to five landmarks were presented ($estimate_{3\text{-}5}=-0.317$, $SE=0.095$, $t(554.450)=-3.343$, $p=.005$). The other comparisons for observer shift were non-significant (one vs five landmarks: $estimate_{1\text{-}5}=-0.169$, $SE=0.094$, $t(553.422)=-1.792$, $p=.221$; one vs three landmarks: $estimate_{1\text{-}3}=0.148$, $SE=0.094$, $t(554.313)=1.568$, $p=.235$). Together, this indicates that allocentric weights decrease when landmarks are less reliable. All allocentric weights were greater than zero (all $p\leq.003$), indicating the use of allocentric cues when reproducing the spatial configuration of balls.

Egocentric weights

The model comparison indicated that a model with random intercept for participants and number of landmarks (one, three, five) as fixed effect fitted the data best. The factor landmark shift did not improve the model fit and consequently no statistics for this factor are reported. However, to facilitate the comparison to the allocentric weights we nevertheless display this factor in Figure 4b presenting the egocentric weights. The egocentric weights were influenced by the number of landmarks ($F(2, 565.237)=5.049$, $p=.007$, $\eta^2=.017$). Post-hoc tests showed that, compared to five landmarks, three (*estimate*$_{3\text{-}5}$=0.073, *SE*=0.025, *t*(565.233)=2.934, *p*=.010) and one (*estimate*$_{1\text{-}5}$=0.062, *SE*=0.025, *t*(565.371)=2.513, *p*=.024) landmarks had higher egocentric weights. The egocentric weights did not differ significantly for the comparison between one and three landmarks (*estimate*$_{1\text{-}3}$=-0.011, *SE*=0.025, *t*(565.104)=-0.429, *p*=.668). These results indicate that the reliance on egocentric cues increases when allocentric cues become less reliable. All egocentric weights were greater than zero (all *p*<.001), indicating the use of egocentric cues to reproduce the spatial configuration.

Configurational error

The model comparison indicated that a model with random intercept for participants, and number of landmarks (one, three, five), observer shift (yes, no) and the respective interaction as fixed effects fitted the data best. The configurational error (Figure 4c) was influenced by the number of landmarks (*F*(1, 1218.989)=45.503, *p*<.001, η^2=.033), the observer shift (*F*(1, 1218.989)=87.686, *p*<.001, η^2=.064) and their interaction (*F*(1, 1218.989)=5.981, *p*=.015, η^2=.004). Post-hoc tests showed that, compared to three landmarks, the availability of one landmark in the test scene produced a more pronounced configurational error when no observer shift occurred (*estimate*$_{1\text{-}3}$=0.025, *SE*=0.010, *t*(1218.970)=2.635, *p*=.009), and likewise when an observer shift occurred (*estimate*$_{1\text{-}3}$=0.054, *SE*=0.007, *t*(1219.029)=7.950, *p*<.001). In addition, shifting the observer compared to no shift increased the configurational error for three (*estimate*$_{yes\text{-}no}$=0.041, *SE*=0.008, *t*(1219.009)=4.889, *p*<.001) and one landmark (*estimate*$_{yes\text{-}no}$=0.070, *SE*=0.008, *t*(1218.970)=8.356, *p*<.001), which indicates that the allocentric spatial representation of the object configuration is influenced by egocentric cues. All configurational errors differed from zero (all *p*<.001). Altogether, presenting fewer landmarks and changing the participants' position increased the configurational error.

Discussion

We investigated the interaction of allocentric and egocentric reference frames in an adapted version of the object-shift paradigm. We manipulated the spatial location of the landmarks and the observer, and varied the number of allocentric cues. We replicated previous studies showing larger systematic placement errors in the direction of landmark shift with an increasing number of landmarks (4; 8). In addition, participants relied more on egocentric cues when fewer landmarks were present. Moreover, we measured participants' errors when reproducing the configuration of balls. Fewer landmarks resulted in increased errors when participants reproduced the spatial configuration of balls. This is in line with the idea that the representation of an object in visual working memory consists of individual features, arranged as hierarchical feature bundle (26). Importantly, configuration errors increased when egocentric shifts were induced, suggesting an influence of egocentric cues on the allocentric memory of object configurations. This finding challenges the idea that objects that are factually independent of the observer's own movements are also processed independently.

Two views, one from a theoretical stance and one from a neurophysiological stance, could explain our findings. From a theoretical stance, it has been argued that all spatial reference frames are egocentric (27). The very moment humans encode spatial configurations, they do so from a certain – egocentric – vantage point. It is therefore in the nature of spatial coding itself that egocentric cues have an impact on how humans encode spatial configurations. From a neurophysiological stance, findings suggest a more complex interplay between brain regions relevant for allocentric and egocentric coding, respectively (11). While distinct regions are associated with individual reference frames, several areas in the frontal and posterior parietal cortex are associated with both reference frames and serve as conversion areas. The integration of allocentric information into the main egocentric processing pathway is assumed to take place between target representation and action planning – a rather early stage that could explain the diffusion of individual object locations and consequently errors when reproducing them (11).

Accordingly, we observed that the number of landmarks had a different impact on the allocentric weights depending on the observer shift. Compared to five landmarks, presenting one landmark when no observer shift occurred and three landmarks when an observer shift occurred reduced the allocentric weights. This indicates that fewer landmarks generally led to lower allocentric weights, in line with previous studies showing an increase of allocentric weights when more landmarks are shifted (4; 8). In addition, participants relied more strongly on egocentric cues when fewer landmarks were presented. Together, this shows that the number of available landmarks influenced the relative contribution of allocentric and egocentric cues. Presenting fewer landmarks likely increases spatial uncertainty which can lead to a stronger reliance on egocentric cues (9). Allocentric and egocentric weights were always greater than zero, showing that participants relied on both spatial reference frames to reproduce the spatial target information.

We took care that shifted and remembered landmark locations do not overlap. Nevertheless, shifting the landmarks could result in a new landmark position that is closer to a previously memorized target position, facilitating swap errors (28). Theoretically, participants could have conflated the updated landmark position with the memorized target position. Placement errors would then occur in the direction contrary to the landmark shift which would have resulted in negative allocentric weights. However, we did not observe such a behavior in our study.

Our results might be limited by the fact that the number of target objects depended linearly on the number of landmarks. With fewer landmarks (i.e., more target objects) the task was more difficult. Subtracting baseline errors from the respective shift conditions when calculating allocentric and egocentric weights should cancel out task difficulty effects, because shift and no shift conditions had similar task requirements (number of landmarks/target objects). In addition, we observed that allocentric weights decreased and egocentric weights increased when fewer landmarks were presented, which speaks against a mere effect of task difficulty. Given the results from allocentric and egocentric weights, we do not expect that increased configurational errors with fewer landmarks can be explained by differences in task difficulty alone. Nevertheless, this could be tested in future studies.

Trials with observer shift were 1000 ms longer than trials without observer shift, which could affect memory performance. Previous findings showed that memory delays of up to 8.5 s did not affect allocentric coding (5), nor did delays of up to 12 s affect egocentric coding (29). As the memory delay in our experiment was well below the above-mentioned delays, it is unlikely that the additional time of the observer shift affected the results.

Previous experiments often restricted participants' movements, for example with a chin rest (4) or a bite bar (9; 29) to ensure a fixed head position. In this experiment, we refrained from such restrictions. This makes the task more natural and allows optic flow to occur in conditions with and without observer shift. One concern might be that the center of expansion of the optic flow pattern, induced by the observer shift, can potentially capture attention (30), which might affect participants' working memory performance. If the optic flow stimulus distracted participants' attention, it is likely that they learned to suppress this stimulus over time, preventing an impact on working memory (31). Further, another study did not find supporting evidence that a lateral optic flow pattern used to simulate an observer shift caused any form of distraction (32). Consequently, no effect on working memory performance could be observed with the inclusion of optic flow (33). This makes it unlikely that optic flow negatively affected participants' working memory performance in our experiment, and is in line with the view that humans update the target positions held in working memory to account for perceived self-motion (34).

In summary, our results show that egocentric cues influence the allocentric spatial memory of object configurations. The relative contribution of allocentric and egocentric reference frames seems to depend on the number of allocentric cues, with stronger allocentric coding when more landmarks are available. This suggests that allocentric and egocentric reference frames do closely interact for memory-guided actions.

Supplemental material

Supplemental Table S1:
https://osf.io/2nv5s/?view_only=082d9e8a22604d1d8cf22d5399255def [*public link will be provided upon acceptance*].

Data availability

Source data for this study are openly available at https://osf.io/2nv5s/?view_only=082d9e8a22604d1d8cf22d5399255def [*public link will be provided upon acceptance*].

Acknowledgements

We would like to thank Yanina Tena Garcia for her support in the data collection process. The work presented here was funded by the German Research Foundation, International Research Training Group, IRTG 1901, “The Brain in Action” and the DFG grant FI 1567/6-1 “The active observer”.

Author contributions

HK designed the experiment and pre-processed the data. PPF analyzed the data and PPF, KF and HK interpreted the results. PPF created the figures and drafted the manuscript. PPF, KF and HK revised the manuscript and HK supervised the project.

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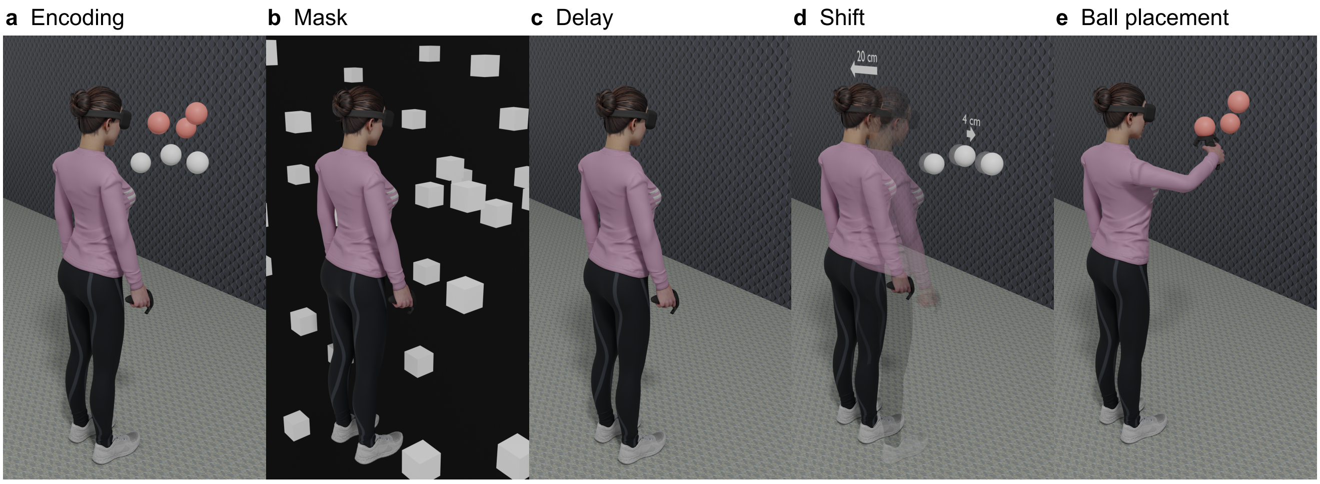
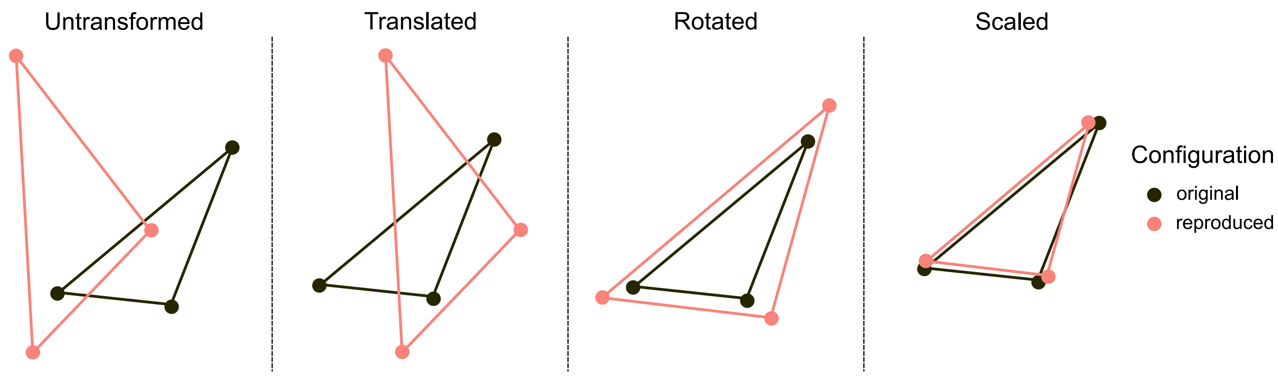
Figure 1. Depiction of a participant performing the experiment. a) A participant encodes the scene in which a configuration of six balls is presented. For illustration purposes, white and coral colored balls represent future landmarks and target objects, respectively. The participant sees all balls in white color and does not know which balls will later be landmarks or target objects. After b) a mask and c) a brief delay, d) either the landmarks, the participant or both are laterally shifted. If both shifts occur, the test scene with the new landmark locations is presented first, followed by the lateral shift of the participant. e) The participant uses the controller to place the target objects at the remembered positions in an empty scene. The avatar model was not visible to participants and was taken from www.mixamo.com.

Figure 2. Illustration of the Procrustes analysis. Black triangles represent the original configuration of balls shown to participants in the encoding scene. Coral triangles illustrate the configuration of balls reproduced by participants. The Procrustes analysis accounts for differences between both configurations by transforming the reproduced configuration of balls. From left to right, the spatial overlap between both configurations increases after translating, rotating and scaling of the reproduced configuration.

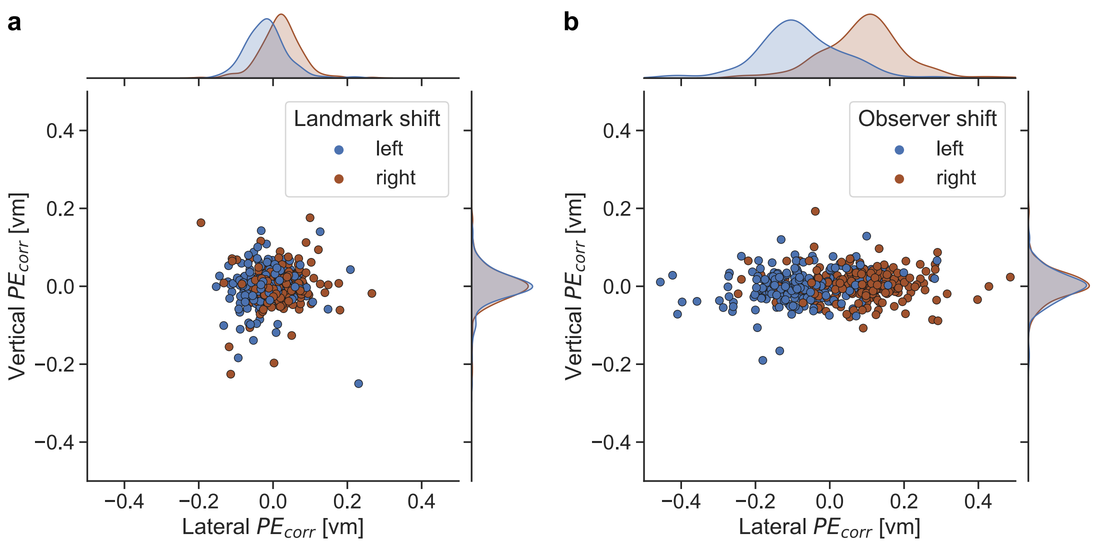
Figure 3. Baseline-corrected placement error (PE_{corr}) in virtual meters (vm) for a) the effect of a landmark shift when no observer shift was present and b) the effect of an observer shift when no landmark shift was present. In the lateral direction, negative values indicate errors towards the left and positive values towards the right. In the vertical direction, negative and positive values indicate downwards and upwards errors, respectively.

Figure 4. Illustration of the results. a) Allocentric and b) egocentric weights are plotted depending on the shift condition and the number of landmarks in arbitrary units (a.u.). Note that the factor landmark shift for the egocentric weights was not significant, but is kept in the visualization to facilitate comparing allocentric and the egocentric weights. c) Shows the configurational error as root-mean-square-error (RMSE) depending on the observer shift. Mean values were calculated on the preprocessed data and can therefore slightly deviate from the model parameters. Individual data points are averaged per participant. Error bars represent the 95% within-subject confidence intervals, accounting for the none-independent data of the repeated-measures design.

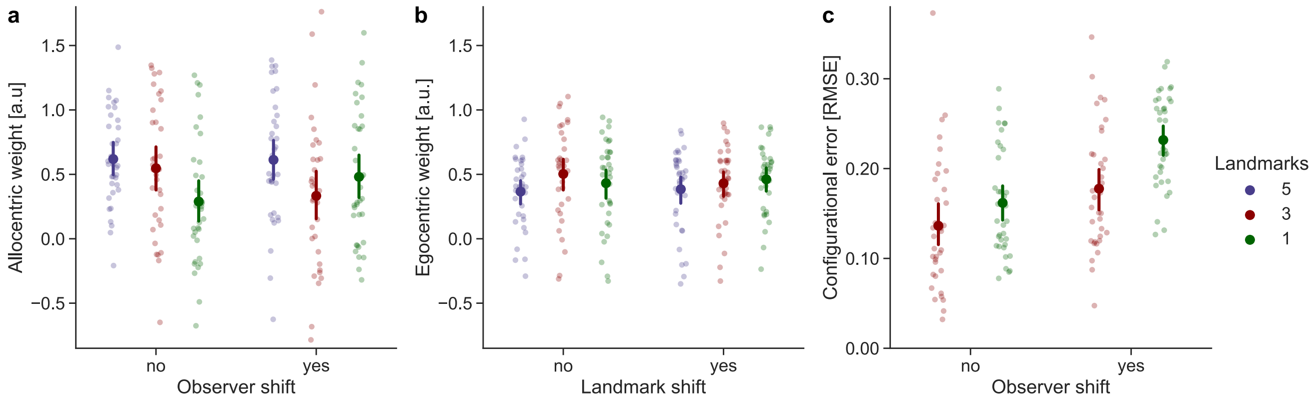

a Encoding
b Mask
c Delay
d Shift
e Ball placement
20 cm
4 cm



Untransformed
Translated
Rotated
Scaled
Configuration
original
reproduced

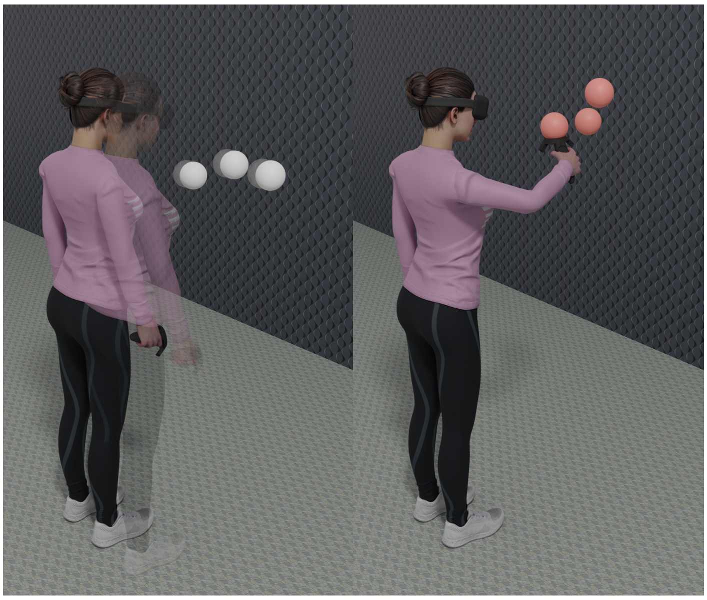


a
b
Landmark shift
left
right
Observer shift
left
right
Vertical PE_{corr} [vm]
Lateral PE_{corr} [vm]
−0.4
−0.2
0.0
0.2
0.4

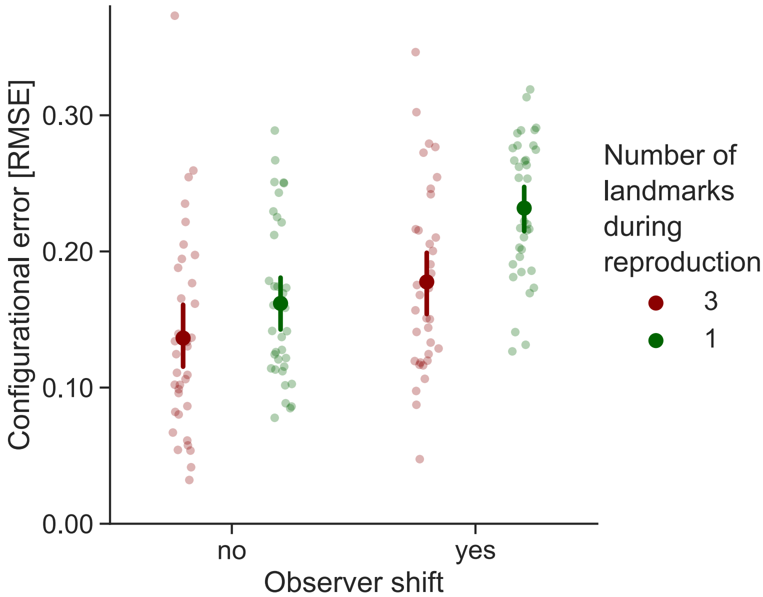

a
Allocentric weight [a.u]
1.5
1.0
0.5
0.0
−0.5
no
yes
Observer shift
b
Egocentric weight [a.u.]
1.5
1.0
0.5
0.0
−0.5
no
yes
Landmark shift
c
Configurational error [RMSE]
0.30
0.20
0.10
0.00
no
yes
Observer shift
Landmarks
5
3
1

Interaction of egocentric and allocentric cues in allocentric spatial coding

Participants reproduced a configuration of balls from memory after a landmark (allocentric) and an observer (egocentric) shift.



Configurational errors describe the spatial overlap between the reproduced and the originally presented configuration.



Conclusion

Egocentric cues influence the spatial memory of object configurations.

Selbständigkeitserklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbständig und ohne unzulässige Hilfe oder Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten oder nichtveröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ niedergelegt sind, eingehalten sowie ethische, datenschutzrechtliche und tierschutzrechtliche Grundsätze befolgt. Ich versichere, dass Dritte von mir weder unmittelbar noch mittelbar geldwerte Leistungen für Arbeiten erhalten haben, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen, und dass die vorgelegte Arbeit weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde zum Zweck einer Promotion oder eines anderen Prüfungsverfahrens vorgelegt wurde. Alles aus anderen Quellen und von anderen Personen übernommene Material, das in der Arbeit verwendet wurde oder auf das direkt Bezug genommen wird, wurde als solches kenntlich gemacht. Insbesondere wurden alle Personen genannt, die direkt und indirekt an der Entstehung der vorliegenden Arbeit beteiligt waren. Mit der Überprüfung meiner Arbeit durch eine Plagiatserkennungssoftware bzw. ein internetbasiertes Softwareprogramm erkläre ich mich einverstanden.

Gießen, den 25. Oktober 2023

Pierre Pascal Forster