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White paper

Embodiment in Extended Reality: Concepts, Challenges and Future Directions

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1 Introduction

Recent technological advancements in the realm of extended reality (XR), such as the advent of virtual reality (VR), augmented reality (AR), and mixed reality (MR), allows humans to inhabit a virtual body distinct from their physical one. Humans perceive themselves as residing within a body that operates in accordance with their intentions and responds to their commands (Kiltner et al., 2012). The interaction between the self and our environment is fundamental to human lives (Forster et al., 2022). Therefore, we are consciously attuned to our body's posture signals (proprioception) and internal bodily cues (interoception), which encompass specific sensations such as hunger, relaxation, or pain (Döllinger et al., 2022; Mehling et al., 2009).

In our daily lives, these bodily sensations merge to create the perception of a single body, our biological one (Kiltner et al., 2012). Thus, our sense of self emerges from our bodily experiences and representations. Given the constant presence of our physical body, it appears unlikely that we can separate our sense of self from it (Kiltner et al., 2012). However, the lingering question remains if we can surpass our sense of self, along with our sense of body, while occupying a virtual form, and if this illusion can be further enhanced (e.g. by integrating multisensorial stimuli in XR). To answer this question, we conducted a literature review tackling what is known thus far on the topic of embodiment in XR environments, both theoretically (i.e. what is embodiment) and methodologically (i.e. how we can measure and evaluate the experience in user research).

The following review will first discuss theoretical concepts such as the sense of embodiment and presence, and how these two concepts are intertwined. We delve deeper into the frameworks of Kiltner et al. (2012) and Haans and IJsselstein (2012) as stepping stones to the integrated framework of Foster et al. (2022), *'the Implied Body Framework'* (IBF). Once we identify the related concepts, we need to be able to influence and measure them in future research. Consequently, we will look at the different sensory stimuli present in XR and their relationship with embodiment (i.e. visual, auditory, haptic and olfactory), and create an overview of the self-report and psychophysiological measures of embodiment that already exist. We conclude with some implications for future research for psychophysiological measurements for embodiment in XR and offer some interesting research questions for future studies.

2 Embodiment: A Literature Review

Embodiment can be defined as the process of integrating bodily entities, such as a rubber arm (de Vignemont, 2011), into the representation of the body – shortly defined as “the subjective experience of having and using a body” (Blanke & Metzinger, 2009). This integration gives rise to experiential properties that shape embodiment, including sensations related to our body, such as ownership, location, and agency (Kilteni et al., 2012; Longo et al., 2008). *Ownership* pertains to the feeling that the body belongs to us; *self-location* involves a perception of where we position ourselves relative to our body; and *agency* entails the feeling of being in control of our own (bodily) actions, of being able to plan and act (Forster et al., 2022; J.-P. Stein & Ohler, 2017).

Initially, manipulating the embodied experience may seem problematic and unrealistic (Kilteni et al., 2012). However, a multitude of studies have unveiled quite the contrary, demonstrating that humans can indeed develop a sense of embodiment within a virtual body and a virtual space. This perceptual transition from the physical body to a virtual one is termed ‘*Sense of Embodiment*’ or SoE (Kilteni et al., 2012). Through this SoE, humans process the characteristics of the virtual body as if they were attributes of their own biological body (Kilteni et al., 2012). Lachmair et al. (2022) therefore define embodiment as the ability to change your character of perspective.

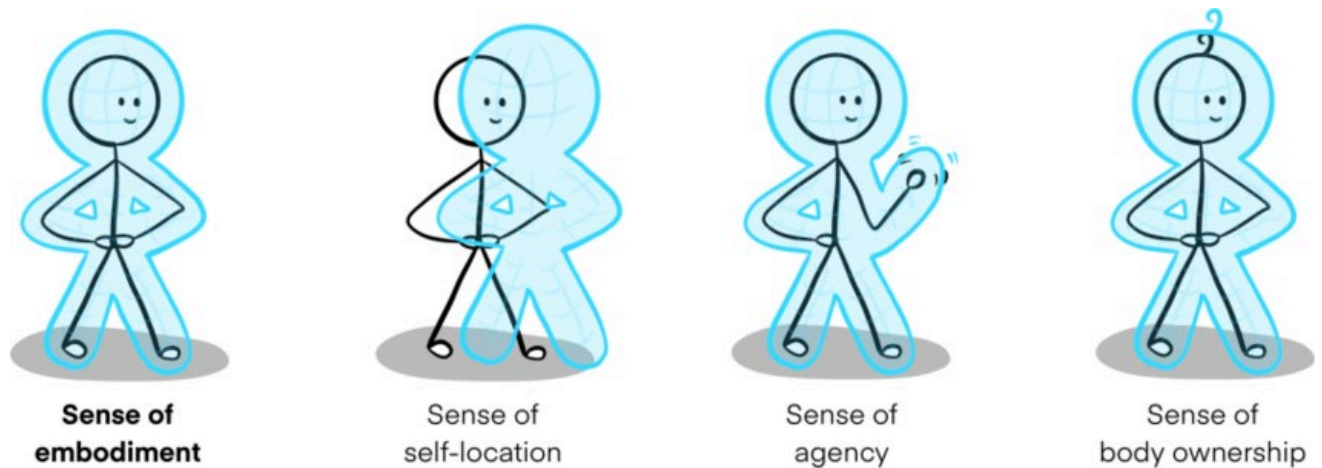


Figure 1 'Sense of embodiment' is composed of the 'sense of self-location', the 'sense of agency', and 'the sense of body ownership'. (Chatain, 2023). Note: This figure was obtained from the dissertation of Julia Chatain (2023) on 'Embodied Interaction in Virtual Reality for Grounding Mathematics'. Permission for non-commercial use is granted.

Building on the work of Tsakiris (2005), Kilteni et al. (2012) define the foundation of SoE as a blend of bottom-up and top-down processing. The bottom-up processing involves visual, tactile, and proprioceptive information that our brain receives through our sensory organs. The top-down processing of information refers to the cognitive procedures that process these sensory stimuli (Kilteni et al., 2012). If an artificial body inhabits sufficient aspects of a human body, our brain can presume this artificial body to be a human body. According to Döllinger et al. (2022) this top-down processing of the virtual body can result in two distinct outcomes.

1. Firstly, it may induce a behavioural shift towards the associated attitudes and behaviours of a non-personalized virtual body, known as the '*Proteus effect*' (Ratan et al., 2020). The Proteus Effect, named after the Greek God Proteus, refers to the phenomenon in online environments where users are influenced by the identities they adopt through their avatars (Yee & Bailenson, 2007). Similar to the concept of deindividuation in psychology, anonymity or reduced social cues online (McKenna & Bargh, 2000), the Proteus-effect can lead to the adoption of new identities inferred from avatars. This effect suggests that users may conform to the expectations and stereotypes associated with their avatars, behaving in ways consistent with these virtual identities (Yee & Bailenson, 2007). Even when users are alone, they may adopt behaviours associated with their avatars. For instance, Yee and Bailenson (2007) demonstrated the Proteus Effect in a study where participants assigned to taller avatars were more confident and assertive in negotiation tasks compared to those with shorter avatars. This can be explained by the self-perception theory, which posits that individuals evaluate themselves from a third-person perspective (Yee & Bailenson, 2007). This Proteus Effect, in which attitudes and behaviours of users match their avatars in the actual and virtual worlds, affirms that completely realistic graphic fidelity might not be necessary (Kyrilitsias & Michael-Grigoriou, 2022).
2. The second outcome of this top-down processing, however, is a result of the degree of realism, particularly photorealism, in virtual bodies. When artificial or virtual bodies bear too much resemblance to human bodies, it could evoke an unsettling sensation, known as the '*Uncanny Valley Effect*' (Mori, 1970; Shin et al., 2019) (see *Figure 2*). This effect occurs when a virtual or artificial body is 'almost' the same as an actual body that the user experience gets 'spooky' (see *Figure 3*). Once observers reach this point, they will no longer perceive this virtual body as their own, but will start to feel alienated by it (C. Stein, 2018). This can result in negative emotions and lead to an aversion towards the virtual body and will ultimately diminish the SoE (Lugrin et al., 2015; Saygin et al., 2012; C. Stein, 2018). According to Misselhorn (2009), this can be corrected but only by very high levels of realism.

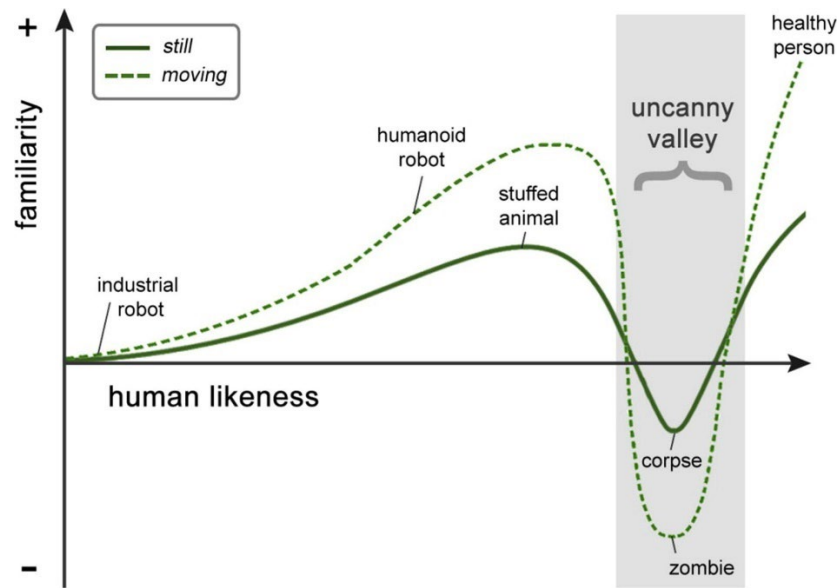


Figure 2 The emotional response plotted against anthropomorphism of a virtual or artificial body. The uncanny valley effect occurs when negative emotions are provoked, depicted by the grey area on the graph. Movement amplifies this emotional response (Mori, 1970).



Figure 3 As an example of 'the uncanny valley effect', on the right half of each picture an actual photograph beside a 3D animated model on the left half (MacDorman & Chattopadhyay, 2016).

2.1 Presence

VR offers a means to introduce users to an alternative virtual body and environment. Within VR, individuals inhabit the presented virtual body and experience a sense of presence within the virtual environment. Consequently, embodiment and presence often coincide and exhibit shared characteristics (Forster et al., 2022).

Shortly, presence can be defined as “the sense of being there” (Slater, 2009)

It's worth noting that various forms of presence exist within virtual environments. These include:

- *Co-presence*, which embodies a sense of togetherness with another individual (Slater et al., 2022).
- *Social presence*, akin to feeling as if one is interacting with another intellectual/intelligent lifeform (Biocca et al., 2003; Glémarec et al., 2022).
- *Spatial presence*, the sensation of being within a virtual environment (Barreda-Ángeles & Hartmann, 2022).

These notions are underpinned by psychological theories revolving around illusion. ‘*The Place Illusion Theory*’ emphasizes the necessity of believing in the depicted VR spaces (Slater et al., 2022). According to Slater et al. (2022), place illusion is the illusion that one is actually present in the environment that is illustrated in a virtual world, even though the person is well aware that this is not true. ‘*The Plausibility Illusion Theory*’ accentuates the importance of events in VR feeling as if they are genuinely occurring (Slater et al., 2022). For instance, rocks falling off a cliff, or an elevator moving from one floor to another. Again, it's the illusion as though this is actually happening even though the user is well aware that this is not the case, and that this is merely a digital rendering of an environment (Slater et al., 2022). Moreover, discussions have extended to exploring how incorporating sonification (i.e. adding audio cues) might heighten a user's sense of presence (Bremner et al., 2022).

A handful of articles have engaged in debates surrounding the concept of presence. Authors in *Presence* have contested a binary understanding of presence, advocating against viewing it solely as a matter of believing or not believing that one is present somewhere, as this perspective oversimplifies the complexity of human cognition (Murphy & Skarbez, 2020). Instead, Murphy and Skarbez (2020) propose directing more attention to the user's active contribution to the overall illusion of the experience.

Another perspective suggests that we should look more into congruence instead of merely looking at presence. Congruence in VR, which refers to the consistency and alignment of sensory information, offers more reliable spatial cues in virtual environments than mere presence (Latoschik & Wienrich, 2022). When the external visual content presented is meticulously aligned with the user's movements and actions, fostering congruence between external and internal perceptions, it generates a cohesive virtual experience. This, in turn, elicits a perception of the VR experience's plausibility and consequently enhances the sense of presence (Latoschik & Wienrich, 2022). Similarly, Hartmann &

Hofer (2022) advocate for considering presence within the broader context of users' general 'media awareness' when engaging with extended reality experiences, rather than assuming complete transport to another space.

2.2 The Relationship between Embodiment and Presence

Whilst prior research did try to relate embodiment and presence, it is still relatively understudied (Forster et al., 2022). Nevertheless, Kilteni et al. (2012) as well as Haans and IJsselsteijn (2012) proposed a framework to study the relationship between embodiment and presence.

In a recent study, Heeter et al. (2020) uncovered a positive correlation between self-reported body awareness and the sense of presence in a virtual environment, albeit their setup lacked a virtual body. Similarly, it has been demonstrated that having a virtual body enhances presence (Jung & Hughes, 2016; Wolf et al., 2021), though without specifically measuring body awareness.

2.2.1 Sense of Embodiment by Kilteni and colleagues (2012)

The framework of Kilteni et al. (2012) addresses the issues of bodily experiences in virtual environments and shows that sense of embodiment is made up of three factors, namely sense of agency, sense of self-location, and sense of body-ownership (see *Figure 1 and 4*).

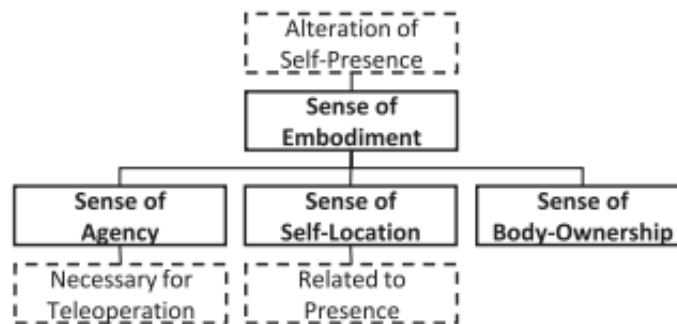


Figure 4 Framework of Kilteni et al. (2012)

Firstly, the *sense of agency* is the subjective experience of initiating, controlling, and being responsible for one's actions. This concept encompasses elements such as motor control, intention, motor selection, and the conscious will to act (Blanke & Metzinger, 2009). Agency is most evident in active movements, where individuals perceive their actions as purposeful and directed (Kilteni et al., 2012). The development of agency heavily relies on visuomotor synchrony, as discrepancies between visual feedback and actual movements diminish the sense of agency (Kilteni et al., 2012). For instance, research of Franck et al. (2001) found that a delay exceeding 150 milliseconds between a movement and its visual feedback significantly reduced participants' sense of agency. This suggests that temporal synchronicity is critical for the development and maintenance of agency, emphasizing the importance of seamless integration between predicted and actual sensory consequences. This

connection between presence and actions suggests that we perceive presence when the virtual environment responds to our actions as expected in the real world (Zahorik & Jenison, 1998). For instance, operating a rover on the moon may induce a sense of presence due to the agency felt when manipulating a joystick and observing immediate consequences on the monitor's displayed image.

Secondly, the *sense of self-location* refers to feeling situated within one's body, while presence involves feeling located in a physical or virtual space, regardless of body representation (e.g., the experience of 'presence' or 'place illusion'; (Slater, 2009). Self-location thus pertains to the relationship between the self and the body, while presence addresses the relationship between the self and the surrounding environment (Kilteni et al., 2012). For example, self-location might involve feeling situated within a biological body or an avatar, whereas presence involves feeling as though one is in a physical or virtual space, independent of a specific body representation.

Self-location heavily relies on visuospatial perspective, typically egocentric (Kilteni et al., 2012). Within this regard, (2004) noted that first-person viewpoints in virtual environments support self-localization by offering sensory evidence of presence in a virtual body. Vestibular signals also contribute, providing information about body motion and orientation relative to gravity (Blanke & Metzinger, 2009). Moreover, tactile input further influences self-location, with the skin serving as a boundary between body and environment.

The brain encodes spaces relative to proximity: personal space (the body), peri personal space (space within reach), and extra personal space (distant space; Halligan et al., 2003; Vaishnavi et al., 2001). These concepts address different aspects of spatial representation and suggest that a broader view of embodiment could encompass presence as a component within self-location (Kilteni et al., 2012).

Last, *sense of body ownership* refers to the self-attribution of a body, characterized by a possessive feeling that the body is the source of experienced sensations (Gallagher, 2000; Tsakiris et al., 2006). According to (Tsakiris, 2010; Tsakiris & Haggard, 2005), body ownership arises from both bottom-up sensory inputs and top-down cognitive processes. Bottom-up influences involve sensory information from visual, tactile, and proprioceptive systems, while top-down influences include cognitive factors like morphological similarity and spatial configuration (Kilteni et al., 2012; Tsakiris, 2010; Tsakiris & Haggard, 2005) (see '2. Embodiment: A Literature Review'). Although, 'the uncanny valley effect' poses a risk to one's experienced ownership of a virtual body, a recent review does suggest that basic morphological similarity is essential for inducing ownership over an external object (Guy et al., 2023).

2.2.2 The Embodiment and Presence Framework of Haans and IJsselsteijn (2012)

Aside from Kilteni et al.'s (2012) framework, we want to delve deeper into the second framework tackling embodiment and presence (see *Figure 3*). The proposed embodiment and presence framework of Haans & IJsselsteijn (2012) integrates (Metzinger, 2006) concept of three orders of embodiment: morphology, body schema, and body image.

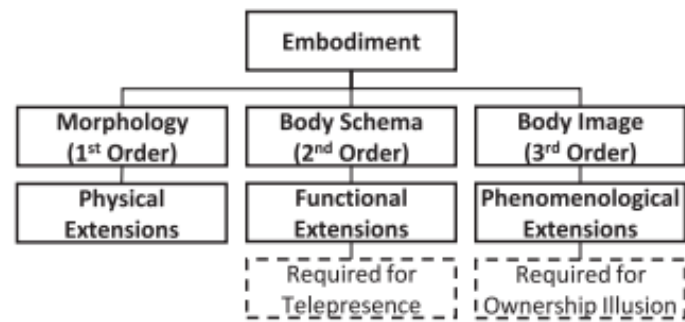


Figure 3. Framework of Haans & IJsselsteijn (2012)

First-order embodiment involves *morphology*, extending to physical properties like mass or form, but lacks a dynamic body schema for proficient tool use. Second-order embodiment includes a *dynamic body schema* enabling fluent interaction with the environment. Third-order embodiment encompasses a *body image and self-consciousness*, enabling conceptualization of one's body over time, such as feeling ownership over an artificial limb.

Haans & IJsselsteijn (2012) argue that presence necessitates interaction with the mediated environment and an adapted body schema, while body image incorporation may not require interaction. However, they suggest that the presence experience may entail a sense of ownership, beyond mere incorporation into the body schema. Forster et al. (2022) asserts that precise characterization of embodiment and presence is lacking. Due to the potential overlap and interconnections between these constructs, there is a need for a collectively agreed-upon, formal definition to advance the field. Forster and colleagues (2022) suggest the development of a conceptual framework called the Implied Body Framework to address this gap.

2.3 Towards an integrated framework: The Implied Body Framework (IBF)

Multisensory integration plays a crucial role in the Implied Body Framework (IBF) (see *Figure 5*), as noted by researchers such as (Botvinick & Cohen, 1998) and (Guterstam et al., 2019). In this framework, Forster, and colleagues (2022) posit that multisensory information signals the potential presence of a body, termed an implied body.

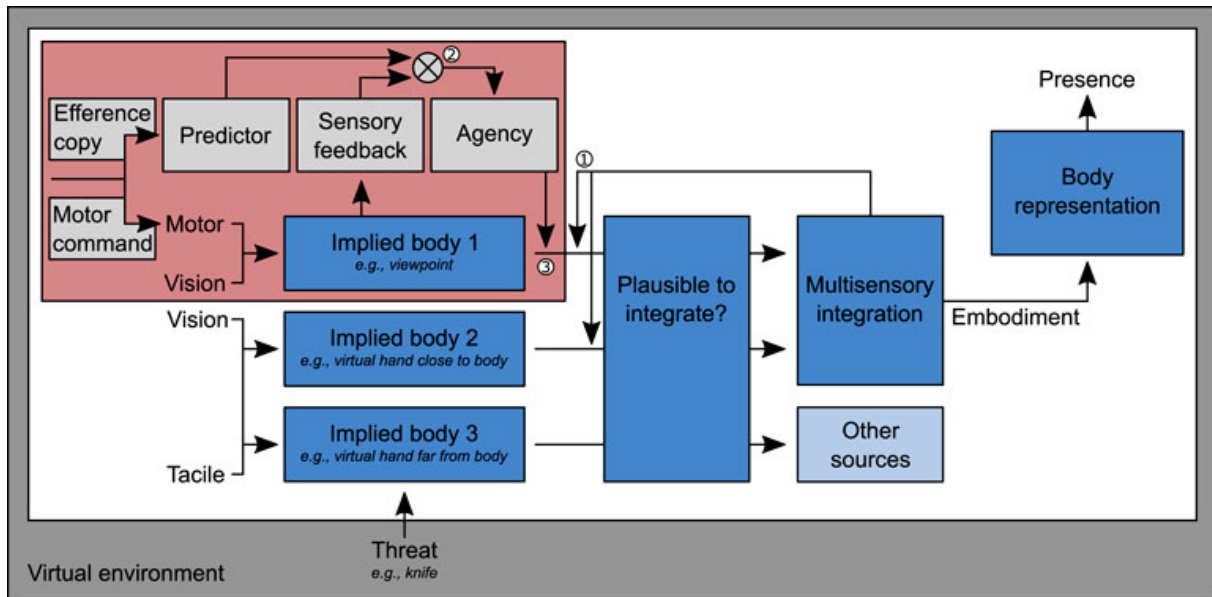


Figure 5 The Implied Body Framework (Forster et al., 2022)

The experience of an implied body arises from coherent patterns across multisensory inputs. For instance, correlations between head movements and visual scene changes create an implied body, demonstrating that it does not necessitate the explicit representation of a (virtual) body, as discussed by (Guterstam et al., 2015). Any multisensory correlation suffices for this purpose, as evidenced by studies like those by (Ehrsson et al., 2005) and (Kalckert & Ehrsson, 2014).

Plausible implied bodies, as proposed by Tsakiris (2010), are integrated into the overall body representation (termed Implied body 1 and 2). During this integration, the implied body is evaluated based on factors such as its shape (as explored by Tsakiris et al., 2010), orientation (as investigated by Ehrsson et al., 2005), and distance from the existing body representation (explored by Kalckert and Ehrsson, 2014).

In other words, when we imagine or mentally represent body parts (called 'implied bodies'), these body parts incorporate into how we picture our own body. During this process, these imagined parts are evaluated based on their shape, position, and distance from our actual body. This blending of imagined parts with our body image creates a sense of embodiment, where the parts feel like they belong to us. At the same time, the feeling of presence relates to where this body image is located in space relative to us.

Forster et al. (2022) propose that multisensory integration (e.g., sound, touch, visuals) can enhance the strength of the body representation and the sense of embodiment. We will discuss these different senses and its relationship to embodiment in the next chapter.

3 Sensory stimuli in XR in Relation to Embodiment

To experience embodiment and related concepts such as presence, several types of sensory cues can add to the experience. We will discuss the relevance of visuals (e.g. visual realism, the visual representation of an avatar), sound, touch, and smell and their relationship to SoE in XR. These factors can be manipulated in XR environments to deepen our understanding of embodiment in future research.

3.1 Visual Realism of Virtual Environments

One of the advantages of virtual reality is that we can transport people to a completely different world. Thus, it makes sense that the way this world is depicted will influence one's experience.

Research has shown that more realistic and detailed worlds lead to higher levels of presence (Hvass et al., 2017). For example, Slater (2009) demonstrated that environments featuring real-time ray tracing, producing accurate shadows and reflections, enhance the sense of presence. Similarly, Jicol et al. (2023) found that visual realism was linked to presence, but the relationship was indirect. In their study, higher visual realism elicited stronger emotional responses (such as fear), which subsequently increased feelings of presence. Additionally, a wider field of vision also enhanced presence, although this effect was influenced by the user's sense of agency.

These results adhere closely to the recent model developed by (Weber et al., 2021), which postulates that presence can be divided into two subcomponents: a sense of being there and a sense of perceived (visual) realism (see *Figure 6*).

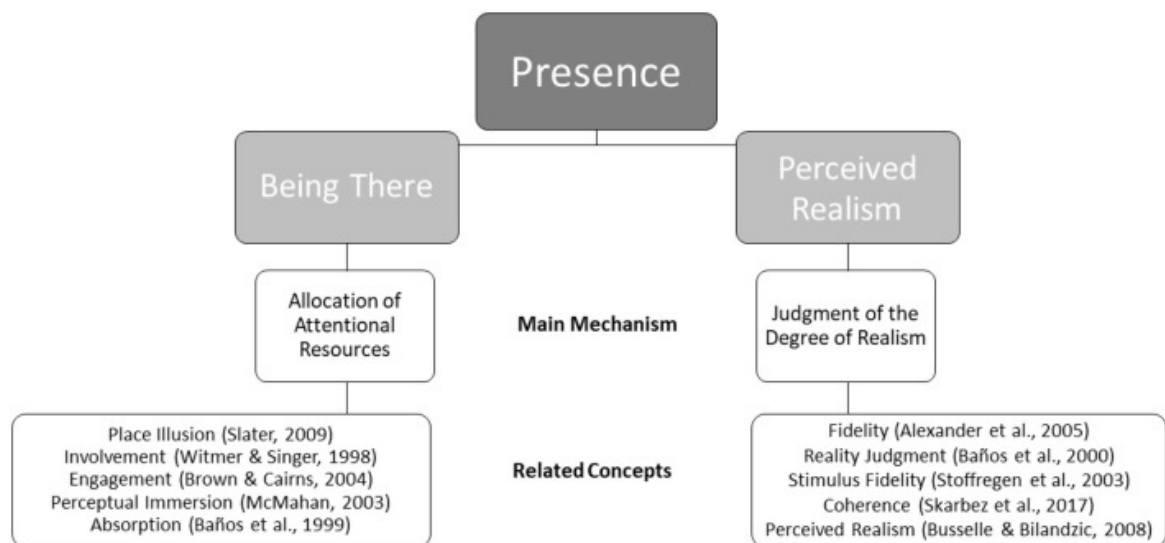


Figure 6 Being there and perceived realism as dimensions of presence (Weber et al., 2021)

“A sense of being there is defined as the allocation of attentional resources to the mediated world and the sensation of perceptually being surrounded by the virtual environment” (Weber et al., 2021, p. 2).

“A sense of perceived realism is defined as the user's individual judgment about the degree of realism of the virtual environment, in terms of virtual objects, sounds and scenes, credibility and plausibility of the story and its characters, and naturalness and ease of the interaction with the virtual environment” (Weber et al., 2021, p. 3).

Jicol et al. (2023) argue that their findings support this model, suggesting that technical factors such as visual realism enhance the sense of presence. This, in turn, fosters emotional responses and a sense of agency, leading to higher levels of perceived realism.

3.1.1 Visual Representation of an Avatar

A key method for enhancing presence and embodiment visually in virtual environments is using virtual avatars. One effective approach is using virtual mirrors, which can increase users' sense of embodiment by making them more aware of their avatar (González-Franco et al., 2014). For example, (Suk & Laine, 2023) demonstrated that participants experienced higher levels of embodiment and body ownership (both for the face and body) when the avatar in the mirror closely resembled their appearance, compared to when it represented a random person. Furthermore, highly realistic avatars have been shown to enhance virtual body ownership (Latoschik et al., 2017) and can even induce a sense of agency over motions that participants did not perform themselves (M. Jung et al., 2022).

(Weidner et al., 2023) conducted a systematic review on avatars in VR and AR, concluding that a full-body avatars positively influence virtual experiences, particularly in terms of presence, social presence, and communication behaviour. They also found that realistic avatar rendering typically outperforms other rendering styles (e.g. abstract, cartoon, ...), especially for fostering embodiment, body ownership, and presence.

However, studies present conflicting findings. For instance, (Lugrin et al., 2018) argued that highly visible or recognizable avatars do not necessarily lead to greater embodiment, and it is possible to induce embodiment without avatars altogether. Fribourg et al. (2020) further highlighted that factors like point of view (first-person versus third person) and avatar control (sense of agency) were rated as more important by participants than realistic appearance. In fact, even a simple stick figure could achieve similar levels of embodiment under optimal configurations. Additionally, in scenarios focused on specific tasks -such as archery in a virtual environment - there was no significant difference in presence, body ownership, or embodiment between different avatar visibility levels or rendering styles (Weidner et al., 2023).

These contradictory results underscore the need for further experimental studies to better understand how visual realism, virtual avatars, and other visual elements interact to influence embodiment and

presence. Carefully designed experiments could help disentangle these complex relationships and advance our understanding of visual realism in virtual environments.

3.2 Auditory Stimuli

Audio can serve various purposes in virtual reality. In their scoping review, (Bosman et al., 2024) examined the diverse uses of audio in virtual reality and its impact on the user experience. Their review highlights that while the relationship between audio and presence has been studied extensively, the findings remain inconsistent. Although, research on the relationship between audio and embodiment is limited, (Sikström et al., 2016) found that audio can enhance the sense of body ownership and agency. For example, when the sounds of a wooden bridge were manipulated, participants adjusted the perceived weight of their virtual character accordingly. Similar studies show that the addition of sound does not necessarily increase the sense of presence (Bialkova & Van Gisbergen, 2017; Sawada et al., 2020). For example, Bosman et al. (2024) concluded in their review that the implementation of audio in virtual environments is not directly linked to presence. However, this conclusion appears preliminary; it may be more accurate to suggest that audio can positively influence presence (or embodiment) in specific contexts, but requires further exploration.

An explanation for these contradictory findings is that the sense of presence in these studies may have already been high due to the visual elements. Additionally, the impact of audio cues might have been closely tied to other sensory stimulations, such as haptics, which could potentially overshadow the influence of audio on presence (Feng et al., 2016).

3.2.1 Different Types of Sound

An intriguing yet unexplored distinction in sound design for virtual environments lies between diegetic, non-diegetic, and trans-diegetic sounds. These terms, widely used in film theory, gaming literature, and VR research, describe how sounds function within a fictional or virtual world (Grimshaw & Schott, 2007; Jørgensen, 2010).

Diegetic sound is perceived by both the user and the in-world characters, thereby fostering a shared auditory experience within the virtual environment. For instance, the sound of birds singing in a virtual forest is audible to both the player and the characters (Jørgensen, 2010). Another example is when a non-player character (NPC) engages in spoken dialogue within the virtual world.

Non-diegetic sounds, by contrast, are audible only to the player, not the characters in the virtual world. Examples include background music or soundtracks that enhance the atmosphere but do not exist within the world itself (Jørgensen, 2010).

Finally, *trans-diegetic sounds* combine elements of both. For example, in *The Lord of the Rings*, there is a scene where Pippin sings a song at a dinner table (*Edge of Night*). While the song is audible to the characters in the room, it transitions into the background soundtrack for the following battle scene.

This dual role - where sound is both diegetic (heard by characters) and non-diegetic (serving as a background) - illustrates the concept of trans-diegetic sound (Sones, 2022).

Although the role of these sound types in shaping presence and embodiment remains understudied, one could hypothesize that diegetic sounds enhance presence and embodiment more effectively than non-diegetic sounds. The addition of diegetic versus non-diegetic sounds - compared to no sound - offers a promising direction for future experimental research on embodiment and presence.

3.3 Haptic Stimuli

Haptic stimulation is widely used in virtual reality research to simulate a sense of touch by applying forces, vibrations, or other types of pressure (Melo et al., 2022). According to Melo et al. (2022), 86.6% of virtual reality studies incorporate some form of haptic feedback, ranging from simple vibrations to more complex stimulations such as thermal or kinaesthetic feedback. Advanced haptic functions are primarily applied in fields of medical training, for example 3D touch for laparoscopic surgery simulation training. Furthermore, (Melo et al., 2022) noted that haptic cues are particularly effective in directing users' attention to virtual notifications, as shown by (Gibo et al., 2014).

Embodiment through haptic feedback is typically achieved by combining tactile and proprioceptive stimulation (Melo et al., 2022). This principle was first demonstrated in the seminal rubber hand illusion (RHI) study by (Botvinick & Cohen, 1998), where participants perceived a rubber hand in their field of vision as their own. When a brush stroked the visible rubber hand, participants reported feeling the touch and identified the hand as part of their body - a phenomenon known as body ownership.

For haptic feedback to successfully integrate sensory information with a virtual body, it must appear plausible (Forster et al., 2022). A critical factor for inducing embodiment in virtual reality is ensuring consistent visuo-tactile sensations (Bovet et al., 2018; Forster et al., 2022). Research has consistently shown that congruent visuo-tactile stimulation enhances presence (Nagao et al., 2018; Viciano-Abad et al., 2014), body ownership (Caola et al., 2018; Choi et al., 2016; Egeberg et al., 2016), and embodiment (McAnally & Wallis, 2022). For example, McAnally and Wallis (2022) found that passive haptics - where users physically touch an object in the real world while interacting with the same object in VR - leads to greater embodiment compared to no haptics or active haptics (haptic feedback delivered through a controller).

Conversely, inconsistencies between visual and tactile feedback can diminish the sense of embodiment. For instance, the RHI does not occur when there is a mismatch in timing or position between the visual and tactile stimuli. Similarly, the rare neurological condition known as floating hand syndrome, where individuals feel a lack of control over their hand's actions, results from a disruption of body ownership (Bovet et al., 2018). (Krogmeier et al., 2019) also demonstrated that incorrect timing or positional inaccuracies between visuals and haptics significantly reduced levels of embodiment.

These findings suggest that consistent haptic feedback - aligned both spatially and temporally with visual cues - enhances embodiment and presence, while inconsistencies degrade the experience. This aligns with the implied body framework proposed by Forster et al. (2022), which posits that more plausible representations of the body are more likely to be integrated into the user's sense of self. Developing haptic feedback that seamlessly fits within virtual experiences is therefore essential for fostering a powerful sense of embodiment.

3.4 Olfactory Stimuli

Research on olfactory stimuli in virtual environments is limited, primarily due to the technical challenges associated with using smell (Melo et al., 2022). Unlike vision, which can be manipulated relatively easily using three-color components, smell involves complex chemical processes that are both difficult to control in experimental settings and technically challenging to deliver (Melo et al., 2022). However, olfactory manipulation has been explored in other fields, such as advertising, where studies have shown that consumers respond more positively to a product when the accompanying scent is congruent with the visual advertisement. For instance, pairing the sight of a chocolate advertisement with the smell of chocolate evokes a favourable response (Gvili et al., 2018).

Despite these challenges, the limited research on olfactory stimuli in VR shows promising potential. Cowan et al. (2023) found that adding smell to a virtual environment enhances both immersion and brand recognition. Similarly, congruent scents - whether pleasant or unpleasant - can increase the sense of presence (Baus & Bouchard, 2017). (Munyan et al., 2016) further observed that presence is enhanced when smell is introduced incrementally, such as adding it in a second phase of an experience. Smell has also been linked to embodiment; for example, (Lesur et al., 2023) found that participants felt a stronger sense of identification with fruit when exposed to a matching scent.

These findings suggest that olfactory stimuli could play a significant role in the future of virtual reality experiences, if advancements in technology make the delivery of smells more accessible and dependable.

4 Measures of Embodiment in XR

4.1 Self-report Questionnaires

Researchers more often rely on self-reported questionnaires when studying embodiment in XR environments in relation to various visual, auditory, and haptic features. Although some concerns exist about using self-report questionnaires to assess perceptual illusions like embodiment, given their subjective and retrospective nature (Slater, 2004), these tools remain the most widely used method. Their popularity stems from their versatility and ease of use (Gonzalez-Franco & Peck, 2018; Guy et al., 2023).

A review of the existing research on embodiment in XR identifies multiple self-report questionnaires designed to measure aspects of embodiment. These questionnaires fall into two main categories:

- 1) **Embodiment of rubber/virtual body parts questionnaires:** These tools focus on assessing the embodiment of rubber or virtual body parts (Botvinick & Cohen, 1998; Kilteni et al., 2012).
- 2) **Standardized embodiment questionnaires for XR:** These questionnaires compile the most frequently used and relevant items from the existing XR embodiment literature and SEO frameworks into comprehensive tools (Gonzalez-Franco & Peck, 2018; Roth & Latoschik, 2020).

4.1.1 Embodiment of Rubber and Virtual body parts

Botvinick and Cohen (1998) originally proposed the RHI and developed an initial nine-item questionnaire to assess the sense of ownership in experimental settings, employing a 7-point Likert scale for evaluation (see *Table 1*).

Table 1. *Rubber Hand Illusion Questionnaire (Botvinick & Cohen, 1998)*

1 = strongly disagree, 7 = strongly agree

It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand touched.

It seemed as though the touch I felt was caused by the paintbrush touching the rubber hand.

I felt as if the rubber hand were my hand

It felt as if my (real) hand were drifting towards the right (towards the rubber hand).

It seemed as if I might have more than one left hand or arm.

It seemed as if the touch I was feeling came from somewhere between my own hand and the rubber hand.

It felt as if my (real) hand were turning 'rubbery'.

It appeared (visually) as if the rubber hand were drifting towards the left (towards my hand).

The rubber hand began to resemble my own (real) hand, in terms of shape, skin tone, freckles or some other visual feature.

Subsequent RHI experiments reused or modified the Botvinick and Cohen's (1998) original questionnaire, tailored to their specific experimental contexts (Argelaguet et al., 2016; Ehrsson et al., 2005; Guy et al., 2023; Lenggenhager et al., 2007; Longo et al., 2008; Normand et al., 2011).

Importantly, as Botvinick and Cohen's (1998) study focused on the sense of body ownership, their questionnaire did not yet include items addressing other components of embodiment. Some ensuing RHI studies have since broadened the scope to include assessments of people's sense of agency and sense of self-location (Guy et al., 2023; Longo et al., 2008). Longo et al. (2008), for instance, employed ten items rated on a 7-point Likert scale with attention to sense of ownership, location, and agency to measure embodiment of a rubber hand (see *Table 2*).

Table 2. *Embodiment of a Rubber Hand Questionnaire (Longo et al., 2008)*

1 = strongly disagree, 7 = strongly agree
Ownership
It seemed like I was looking directly at my own hand, rather than at a rubber hand.
It seemed like the rubber hand began to resemble my real hand.
It seemed like the rubber hand belonged to me.
It seemed like the rubber hand was my hand.
It seemed like the rubber hand was part of my body.
Location
It seemed like my hand was in the location where the rubber hand was.
It seemed like the rubber hand was in the location where my hand was.
It seemed like the touch I felt was caused by the paintbrush touching the rubber hand.
Agency
It seemed like I could have moved the rubber hand if I had wanted.
It seemed like I was in control of the rubber hand.

The RHI studies described so far have focused their experiments on the embodiment of rubber hands. However, there has also been an increase in research investigating embodiment in VR, applying embodiment not only to physical body parts, but also to virtual body parts in immersive, virtual environments (Guy et al., 2023; Kiltner et al., 2012). Kiltner et al. (2012) developed a questionnaire on the sense of ownership specifically for a virtual arm. They based their questionnaire on that of Botvinick and Cohen (1998), to be answered on a 5-point Likert scale (see *Table 3*).

The iterative modification of Botvinick and Cohen (1998) questionnaire has thus resulted in a diverse array of questionnaires within the field. While enriching the methodological toolkit for assessing the sense of embodiment, this also presents challenges for comparing outcomes across different studies (Guy et al., 2023). That is why researchers are increasingly looking to develop standardized questionnaires by consolidating the most frequently encountered and pertinent items identified across the literature on embodiment in XR (Gonzalez-Franco & Peck, 2018; Guy et al., 2023; Roth & Latoschik, 2020).

Table 3. *Ownership of a Virtual Hand Questionnaire (Kilteni et al., 2012)*

1 = completely disagree, 5 = completely agree
It seemed as if I were feeling the touch of the box in the location where I saw the virtual hand touching.
It seemed as though the touch I felt was from the box being touched by the virtual hand.
I felt as if the virtual arm were my arm.
It felt as if I might have more than two arms.
It seemed as if the touch I was feeling came from somewhere between my real and the virtual hand.
It felt as if my real arm were becoming longer.
I had the feeling that I might be harmed if the saw touched the virtual arm.

4.1.2 Standardized Embodiment Questionnaires

A first example of a standardized questionnaire is the Virtual Embodiment Questionnaire (VEQ) developed by (Roth & Latoschik, 2020). Roth and Latoschik (2020) reviewed existing literature to identify relevant constructs and questionnaire items relating to SoE in VR, and performed confirmatory factor analysis on the data from three experiments.

The resulting questionnaire measures virtual embodiment as consisting of three factors: ownership (i.e. the perception of the virtual body as the own, as the source of all sensations), agency (i.e. the perception of control over the virtual body, and through that, control over events in the environment), and change (i.e. the perceived change in the body schema). Each factor is measured by four items, with responses recorded on a 7-point Likert scale. A fourth study was conducted to confirm the reliability and validity of the questionnaire (see *Table 4*).

Table 4. *Virtual Embodiment Questionnaire (Roth & Latoschik, 2020)*

1 = strongly disagree, 7 = strongly agree
Ownership
It felt like the virtual body was my body.
It felt like the virtual body parts were my body parts.
The virtual body felt like a human body.
It felt like the virtual body belonged to me.
Agency
The movements of the virtual body felt like they were my movements.
I felt like I was controlling the movements of the virtual body.
I felt like I was causing the movements of the virtual body.
The movements of the virtual body were in sync with my own movements.
Change
I felt like the form or appearance of my own body had changed.
I felt like the weight of my own body had changed.
I felt like the size (height) of my own body had changed.
I felt like the width of my own body had changed.

In addition to the VEQ, Gonzalez-Franco and Peck (2018) also worked towards a standardized embodiment questionnaire that measures users' avatar embodiment in first-person VR experiences. According to these authors, embodiment is the feeling (or illusion) that the own body has been substituted by the avatar, and that the new body is the source of the sensations. They propose that embodiment is determined by six aspects, namely *body ownership* (i.e. the user's perception of owning the avatar's body), *agency and motor control* (i.e. the user's perception of being able to control the actions of the body), *tactile sensations* (i.e. the user's ability to feel the tactile sensations/touch directed to the body), *location of the body* (i.e. the perceived location of the avatar in relation to the own body), *external appearance* (i.e. the appearance of the avatar, in terms of looks, clothing, shape, gender, race, age,...), and *response to external stimuli* (i.e. that modify or threaten the body or body parts of the avatar). To evaluate these six aspects, the questionnaire comprises twenty-five items, each measured on a 7-point Likert scale ranged from 'strongly disagree' and 'strongly agree'.

Table 5. Avatar Embodiment in first person VR environments Questionnaire (Peck & Gonzalez-Franco, 2021)
1 = strongly disagree, 7 = strongly agree OR 1 = never, 7 = always

I felt out of my body. [Appearance]
I felt as if my (real) body were drifting toward the virtual body or as if the virtual body were drifting toward my (real) body. [Appearance]
I felt as if the movements of the virtual body were influencing my own movements. [Appearance & Multi-sensory]
It felt as if my (real) body were turning into an 'avatar' body. [Appearance & Response]
At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw. [Appearance & Ownership]
I felt like I was wearing different clothes from when I came to the laboratory. [Appearance & Response]
I felt as if my body had changed. [Response]
I felt a _____ sensation in my body when I saw _____. [Response]
I felt that my own body could be affected by _____. [Appearance & Response]
I felt as if the virtual body was my body. [Ownership]
At some point it felt that the virtual body resembled my own (real) body, in terms of shape, skin tone or other visual features. [Ownership]
I felt as if my body was located where I saw the virtual body. [Ownership & Multi-sensory]
I felt like I could control the virtual body as if it was my own body. [Ownership & Multi-sensory]
It seemed as if I felt the touch of the floor in the location where I saw the virtual feet touched. [Ownership & Multi-sensory]
It seemed as if the touch I felt was caused by the floor touching the virtual feet. [Response & Multi-sensory]
It seemed as if my feet were touching the virtual floor. [Appearance & Multi-sensory]

(Peck & Gonzalez-Franco, 2021) refined their questionnaire later, performing exploratory factor analysis on data collected in nine experiments. Non-universal questions, redundant questions, and questions that were too strongly correlated with other questions were eliminated. This resulted in an updated questionnaire consisting of four interrelated categories, namely *Appearance* (i.e. the visual

alignment of the avatar with the user's body), *Response* (i.e. the user's perception of their virtual body's responsiveness to actions in the virtual environment), *Ownership* (i.e. the user's psychological identification with the virtual body as their own), and *Multisensory* (i.e. the integration of multiple sensory modalities to reinforce the sense of embodiment). These four categories are measured by sixteen items on a 7-point Likert scale (see *Table 5*).

We can conclude that self-report questionnaires are thus widely used, despite Slater's (2004) concerns about using such tools to measure perceptual experiences. Considering questionnaires on embodiment have a potential risk of bias (e.g. social desirability, neutral or extreme answers, not understanding the questions, recall bias; (Halbig & Latoschik, 2021), additional and objective measures during XR experiences are needed (Suh & Prophet, 2018). Luckily, several embodiment experiments using questionnaires as well as psychophysiological measures have shown correlations (González-Franco et al., 2014; Padrao et al., 2016) which advocates for the use of self-reported questionnaires as a valid and easy to use measure for SoE in XR .

4.2 Psychophysiological Measures

To overcome the limitations of self-report measures and gain deeper insights into the physiological underpinnings of embodiment, XR researchers often turn to psychophysiological measures. These methods offer objective, quantitative data on the body's responses to virtual stimuli, providing a complementary perspective to self-reported experiences and enabling a more comprehensive understanding of embodiment in XR environments.

An essential part of our bodily reactions to external stimuli is the autonomous nervous system, which consists of the (ortho)sympathetic and the parasympathetic nervous system. When the *(ortho)sympathetic nervous system* is activated, it is most commonly recognized as 'fight or flight' reactions (e.g. increased heart rate, breathing and blood pressure, pupil and bronchial dilation and increased sweat secretion (Martini & Bartholomew, 2017; Massaro & Pecchia, 2019). A stimulation of the *parasympathetic nervous system* is necessary for relaxation, rest and recovery of the human body and mostly induces opposite effects to the sympathetic nervous system (e.g. slowing down breathing and heart rate; Martini & Bartholomew, 2017; Massaro & Pecchia, 2019).

In everyday life, the nervous system continuously processes and reacts to multisensory information, shaping both psychological and physiological responses. This dynamic interplay becomes particularly relevant in XR, where users can relate to virtual representations as extensions of their biological selves (Kilter et al., 2012). Understanding whether and how the body reacts to virtual stimuli, and similar to real-world stimuli is imperative for research on embodiment in XR.

Although it builds upon earlier research derived from the RHI (Botvinick & Cohen, 1998; Ehrsson et al., 2005), research on psychophysiological responses as an indicator of embodiment is relatively recent (Czub & Kowal, 2019; González-Franco et al., 2014; Kokkinara et al., 2016; Macaudo et al., 2015; Škola & Liarokapis, 2016; Tieri et al., 2017). For example, electroencephalography (EEG) has

been used to study body ownership, localisation and agency in XR environments (González-Franco et al., 2014; Padrao et al., 2016; Škola & Liarakapis, 2016). Similarly, skin temperature has been explored as a measure of ownership and agency (Macauda et al., 2015; Tieri et al., 2017). Electrocardiography (ECG) and electrodermal activity (EDA) have been combined with assessments of ownership, self-localization, movement perception and agency (Kokkinara et al., 2016). Other physiological measures include respiration rate, tidal volume, and heart rate, which have been correlated with self-reported experiences of ownership, self-localization, movement perception, agency, and self-identification (Aspell et al., 2013; Betka et al., 2020; Czub & Kowal, 2019; Kokkinara et al., 2016). Finally, pupil diameter (PD) has been investigated as a psychophysiological indicator of embodiment, measured alongside self-reported questionnaires (Falcone et al., 2022).

4.3 Towards Practical and Inclusive Psychophysiological Approaches

Measuring psychophysiological responses in XR research often relies on advanced technologies such as EEG, EDA, and ECG. While these tools provide detailed and reliable data, they are typically expensive, technically demanding, and time-intensive, requiring significant expertise for analysis, interpretation, and application. This complexity entails that often healthcare professionals and/or other domain experts must be involved to ensure accurate conclusions. For designers and developers, however, the ability to quickly and efficiently assess the psychophysiological effects of new XR applications is crucial, especially in iterative R&D processes like rapid prototyping and design thinking.

Additionally, there is a parallel need for cheap, easy to use physiological measures to conduct (large) randomized controlled trials in sectors such as education and health care, for instance, to support and improve quality of care or learning outcomes. When new IVR applications are being developed the extent to which they adequately immerse, and therefore show high levels of presence and embodiment, could be fundamental to achieve the effect for which they were designed (e.g. reduction of anxiety or pain in patients, increased learning motivation and learning outcomes, ...) (Suh & Prophet, 2018).

Furthermore, most current psychophysiological studies focus on measuring embodiment through negative or stress-based stimuli, such as perceived threats (Falcone et al., 2022; González-Franco et al., 2014; Halbig & Latoschik, 2021). We advise to expand this research by exploring positive experiences, including relaxation, excitement, and enjoyment. Investigating how positive stimuli influence embodiment could provide a more comprehensive understanding of user engagement and broaden the applications of XR in both research and practice.

5 Conclusion: Charting the Future of Embodiment in XR

This white paper explored the multifaceted nature of embodiment in XR, delving into theoretical frameworks, sensory stimuli, and measurement methodologies. Core insights include the intricate interplay between presence and embodiment, the foundational role of sensory integration, and the potential of frameworks like the Implied Body Framework (Forster et al., 2022) to advance our understanding of the subjective experience of embodiment.

Key opportunities for future research include refining the technical and psychological components of sensory stimuli—visual, auditory, haptic, and olfactory—to deepen the sense of embodiment. Investigating the nuanced roles of congruence and plausibility in fostering embodiment offers a promising avenue to design more engaging and immersive XR experiences.

Additionally, while self-report measures remain central, the adoption of psychophysiological methods holds promise for capturing more objective data on user experience. However, practical challenges such as accessibility and cost must be addressed to make these methods feasible for broader applications in fields like healthcare, education, and entertainment.

Building on these insights, several key research questions emerge, highlighting opportunities to deepen our understanding of embodiment in XR and advance its application across diverse domains. These include:

Sensory integration and realism:

- How do visual, auditory, haptic, and olfactory stimuli interact to shape the sense of embodiment?
- What levels of realism (e.g., photorealistic avatars, spatial sound) optimize embodiment without triggering adverse effects, such as the uncanny valley?
- How can congruence and plausibility in multisensory feedback be operationalized to enhance embodiment?

Interplay between presence and embodiment:

- What are the precise mechanisms through which embodiment enhances presence, and vice versa?
- How can XR environments balance user awareness of virtuality with immersion to strengthen presence and embodiment?

Measurement innovations:

- Can psychophysiological measures such as EEG, skin conductance, or heart rate variability be standardized for assessing embodiment across diverse XR applications?

- How do self-reported experiences correlate with physiological data in understanding embodiment dynamics?
- How can low-cost, scalable tools be developed to measure embodiment, making research accessible to domain specific researchers (e.g. education, health care, entertainment, ...) and developers?

Positive and task-specific embodiment:

- How do psychophysiological reactions to positive virtual experiences, such as relaxation, enjoyment, and engagement, affect embodiment?
- What role does embodiment play for specific aspired outcomes of virtual environments, such as skill acquisition or therapeutic interventions?

In conclusion, the study of embodiment in XR stands at an exciting intersection of technology and human experience. By addressing these challenges and seizing opportunities, researchers and developers can unlock the potential of XR to enhance presence and embodiment in virtual environments.

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