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Enhancing bodily self-consciousness in the virtual world with synchronous multisensory stimulation, interoceptive feedback and peripersonal space expansion: A narrative review

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ABSTRACT

The article explores the link between neuroscience and the design fields by discussing works on predictive brain, conscious mind, perception, and peripersonal space to increase bodily self-consciousness in the virtual world. Unlike the physical reality, the virtual world often lacks the intricate bodily feedback necessary for self-consciousness, thus resulting in less complete virtual representations. By incorporating findings from neuroscience and the virtual world, this research suggests a theoretical approach to enhance bodily self-consciousness in different virtual worlds, particularly augmented or diminished mixed realities and holistic virtual reality. This is achieved through synchronous multisensory stimulation (visuo-tactile), interoceptive feedback, and peripersonal space expansion (visuo-tactile and audio–tactile). As a narrative review, the article not only suggests a theoretical method but also highlights the potential for future practical experiments to apply these insights.

Definition of terms

Below are definitions of pivotal concepts to afford readers a comprehensive grasp of the terminology:

Predictive brain – Brains continuously make predictions about the world and the self. These predictions are then compared to incoming data, combined with prior beliefs. Differences between predicted signals and actual data, called prediction errors, are used to update prior beliefs and prepare for the next round of inputs. Most of the time, these predictions correspond to the actions that the system is taking or planning to take, making them active rather than passive inferences (Hoemann et al., 2017; Seth, 2021).

Conscious mind – Mental experiences are deeply rooted in the interaction between the mind and the body. For some neuroscientists, the mind becomes conscious when images providing information to the organism about the internal state of the body (interoception) are included, such as heart rate, blood pressure, breathing patterns and muscular contractions (Carvalho & Damasio, 2021; Damasio, 2022; Seth, 2021).

Interoceptive feedback – Interoception represents the state of the body (Feldman et al., 2024). Interoceptive signals arise from many different physiological systems. The cardiovascular system is most commonly studied, as in the example below (MarshallGentsch-EbrahimzadehSchütz-Bosbach, 2022).

Cardio-visual feedback – Schaefer et al. (2014) used a heartbeat training procedure in which participants received visual biofeedback of their beating heart in the form of an animated red heart to improve their heartbeat perception. Since then, several studies have employed visual cardiac biofeedback methods, based on participant's visual feedback (Meyerholz et al., 2019; Schillings et al., 2022; Suzuki et al., 2013) or real-time haptic feedback systems (Dobrushina et al.).

Multisensory integration – the process that enables information from multiple senses to combine in a non-linear manner to reduce environmental uncertainty, such as the combination of vision, touch and breathing patterns (Saltafossi et al., 2023).

Synchronous multisensory stimulation – refers to the practice of presenting stimuli to different senses at the same time and in a coordinated way. For example, the stroking of an artificial hand synchronously with a participant's real hand, while visual attention is focused on the artificial hand (visuo-tactile), leads the participant to experience the artificial hand as part of his or her own body (Suzuki et al., 2013; Botvinick & Cohen, 1998).

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Peripersonal space – the space that lies within reach, our immediate space. It extends around the body and is continuous with personal space (Brozzoli et al., 2012; Livi, Lanzilotto, Maranesi, & Bonini, 2019). Peripersonal space can be enlarged or contracted in the physical (Campbell, 2007) and the virtual world (Noel et al., 2015; Petrizzo, Mikellidou, Avraam, Avraamides, & Arrighi, 2024).

1. Introduction

Neuroscientific research has been significantly developing, especially in the last 50 years (Altimus et al., 2020). The article examines the ways neuroscience can inform the design of new virtual worlds by discussing how embodiment affects bodily self-consciousness and presenting works and experiments related to predictive brain, conscious mind, perception and peripersonal space to increase bodily self-consciousness in the virtual world.

There has been a noticeable increase in interest in the mechanisms underlying body self-consciousness within the past 20 years (Dary & Lopez, 2023). This interest arises from the development of virtual worlds that aggregate while we live, play, work, connect, and learn more online (Boczkowski, & PabloMitchelstein, 2021). David Chalmers says that we might be living already in a simulation. As a philosopher, he defines terms such as "virtual world," as an interactive computer-generated world that can be immersive or not. For him, simulations, such as the virtual world and immersive virtual reality, are a form of reality (Chalmers, 2022). Following Chalmers's definition, the article makes use of the term "virtual world," and includes different digital domains (two-dimensional or three-dimensional), which will be properly defined later.

A significant difference between the physical and the virtual world concerns the understanding of objects. When designers create an object in the physical world, they bear in mind an object's shape, functionality, and compatibility with the human body. When they do it virtually, the object's function takes precedence over its shape and how it interacts with the human body. As there is no direct relationship with the physical world, the comprehension of virtual objects decreases, which means that the appearance and utility of virtual objects are not necessarily connected (Goble, 2010). In addition, in the virtual world, some of the sensory inputs crucial for self-recognition are lost, such as proprioceptive, tactile, motor, and visual. These inputs, readily available in the physical world, are exemplified by the fact that when we gaze in the mirror, we frequently move or touch our faces (Tsakiris, 2008).

The integration within these two realms is still complex, especially considering that the body's perception is severely restricted in the virtual world. However, technological advancements are revising the old distinctions between the physical and the virtual worlds by enhancing the body's perception in the virtual world and improving user experience. This tendency is supported by significant research from neuroscientific works and experiments.

Neuroscientific experiments demonstrate how simultaneous visuotactile stimulation might improve self-identification with (a) another person's face (Sforza et al., 2010; Suzuki et al., 2013; Tsakiris, 2008); (b) a fake physical rubber hand (Botvinick & Cohen, 1998; Craig, 2003; Seth, 2017); (c) a fake virtual hand (Suzuki et al., 2013); (d) a whole virtual body (Lenggenhager et al., 2007); (e) a whole virtual body with peripersonal space (Noel et al., 2015); (f) or someone else's body (Ehrsson, 2007; Suzuki et al., 2013; Yong, 2011). These experiments, complemented by other neuroscientific works, offer new opportunities for understanding the creation of virtual worlds more aligned to the body and its physiology. Within this context, this article explores how bodily self-consciousness can be enhanced in the virtual world. Specifically, it delves into three important aspects: synchronous multisensory stimulation, interoceptive feedback and peripersonal space expansion.

Building on the above experiments and complemented works, the research suggests that synchronous multisensory stimulation has the potential to update cognitive representations of self-recognition and ownership. Furthermore, synchronous interoceptive feedback can play a crucial role in enhancing the experience and effectiveness of synchronous multisensory stimulation. Additionally, not only the body but also peripersonal space can be used in the virtual world as part of our extended body. Collectively, these three aspects enhance self-consciousness in virtual worlds and foster the integration of physical and virtual worlds.

This theoretical article, with a narrative review method, aims to explore new design possibilities in the virtual world by discussing existing neuroscience research and raising intriguing questions along the way, rather than providing particular solutions.

2. Types of virtual worlds

Following the xReality framework (XR), the variable x serves as a placeholder for Augmented, Assisted, Mixed, Virtual, Atomistic Virtual, Holistic Virtual, or Diminished Reality. This framework distinguishes between Augmented Reality (AR) and Virtual Reality (VR), whether the user's experience is influenced by the physical environment. If so, the experience is AR; if not, it is VR (Philipp et al., 2022).

The xReality framework also offers two continua to define AR and VR in more detail: the AR continuum ranges from assisted to mixed reality, with local presence serving as the primary differentiation between poles. Local presence is defined as the degree to which a user experiences AR objects as being actually present in his or her own physical environment (Philipp et al., 2022).

In assisted reality, the purpose of the virtual objects is to assist the user in obtaining a better understanding of the physical environment rather than to merge virtual objects with the real world. For example, maps with overlaid information for places of interest when on a sightseeing tour. In mixed reality, real and virtual realities merge and, in their extreme form, become indistinguishable to the user. For example, apps that track and map the environment in three dimensions, and integrate digital objects realistically and seamlessly into the user's perception of the real world (Philipp et al., 2022).

Diminished Reality when at the assisted reality endpoint, uses an unrealistic overlay, for example, such as a censor bar blurring content. When at the mixed reality endpoint, diminished reality seamlessly removes the perception of a real object in a way that is challenging or impossible to notice by users (Philipp et al., 2022).

Within this perspective, it is important to realize that mixed reality is not inherently "better" than assisted reality; this depends on the general context. User goals determine whether users perceive one specific AR application as being better than another one. However, local presence is more significant in mixed reality, either in augmented or diminished realities.

The VR continuum ranges from atomistic to holistic, and the level of telepresence serves as the primary differentiation between poles. Telepresence refers to presence mediated through a fully virtual environment (Philipp et al., 2022).

Atomistic VR refers to applications of VR in which achieving a goal frequently takes precedence over the quality of the user experience. For example, when VR is used for training or modeling physical spaces, in which the completion of a task is a priority. In these situations, accomplishing a particular objective or outcome is more significant than the user's perception of telepresence. Holistic VR is characterized by a VR experience that, in the user's mind, is almost identical to a real-world encounter. In these situations, the perception that the user feels present in the virtual world takes precedence over other factors. Therefore, telepresence is more important in Holistic VR (Philipp et al., 2022).

In conclusion, bodily self-consciousness affects all of these different types of virtual worlds to a minor or greater extent. However, those in which bodily self-consciousness is more taken into consideration might be the ones in which local presence and telepresence are greater, such as in augmented or diminished mixed realities, and holistic virtual reality.

3. Bodily self-consciousness as predictive

3.1. Interoception as an important type of predictive perception

Perception comprises three essential parts: exteroception, proprioception, and interoception (Audi, 2004; Barrett & Simmons, 2015; Craig, 2002; Damasio, 2021; Seth, 2017). The first one is exteroception, which is the perception of an organism's exterior and is mediated by exteroceptive senses (hearing, touch, smell, taste, and sight) (Damasio, 2003; Seth, 2017).

The second is proprioception, which is our ability to perceive the location, movement, and action of the parts of the body, such as the perception of the joint position, muscle force, and effort (Taylor, 2009; Carvalho & Damasio, 2021; Craig, 2002; Parvizi & Damasio, 2001; Stillman, 2002; Suzuki et al., 2013). Proprioception is an adaption of the body to facilitate the best possible interaction with the environment (Carvalho & Damasio, 2021). Therefore, perception entails both receiving and acting on environmental information (Carvalho & Damasio, 2021; Parvizi & Damasio, 2001).

According to research, self-actuated movement is necessary in order to develop normal visual perception with depth, for example. Our bodily movement provides the dimension of depth to mere visual sensations; movement is the key to understanding the vision (Hein, Held, & Gower, 1970). For instance, if someone picks an animal, like a cat, and carries it around in the world while it is growing up, it will not develop normal vision because it becomes apparent that, at least for mammals, feedback from our bodily movements is required to provide meaning to what is seen. Sensation is only meaningful as it relates to embodiment (Campbell, 2007). This happens because the cat is deprived of self-actuated movement and cannot develop depth perception. Thus, the change of patterns in the visual field does not have a spatial meaning for the cat, and its vision is not normal.

The third is interoception, the perception of an organism's interior, for example, heart rate and the degree of contraction of visceral muscles. Interoception is usually overlooked; however, it is crucial because it gives insight into the workings of the body's interior and helps maintain physiological integrity, homeostasis and the emotional experiences that accompany them (Seth, 2017). Homeostasis is described as a self-regulating mechanism that allows an organism to retain internal stability while responding to changing external conditions (Damasio, 2021; Seth, 2017).

Exteroception is essential for enhancing bodily self-consciousness, especially regarding the use of synchronous multisensory stimulation (visual-tactile) (Botvinick & Cohen, 1998; Craig, 2003; Lenggenhager et al., 2007; Noel et al., 2015; Seth, 2017; Suzuki et al., 2013). However, recent debates in neuroscience and their emphasis on interoception and proprioception have made embodiment become increasingly important (Barrett, 2018; Campbell, 2017; Craig, 2009; Damasio, 2010; Seth et al., 2012; Suzuki et al., 2013).

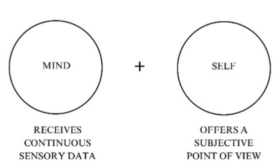

Fig. 1. Conscious mind for Damasio.

3.2. Bodily self-consciousness rooted in interoception

According to neuroscientist Antonio Damasio, the conscious mind is made up of the mind that receives continuous sensory data both from our senses (exteroception) and the self (interoception), (Fig. 1) (Damasio, 2005, 2022).

Due to this, he highlights that changes in the state of the body during and just before the perception of an object can significantly impact subjectivity. As a result, a representational object, a responsive organism, and a self-evolving state caused by the organism's response to the object are all stored in working memory (Damasio, 2005, 2022). He also highlights the importance of the body and the environment in which it resides (Carvalho & Damasio, 2021; Damasio, 2005, 2021).

Damasio also explains that the interoceptive process starts with the peripheral detection of visceral or humoral homeostatic alterations and leads to homeostatic feelings, while the exteroceptive process results in emotions (Fig. 2). Consequently, in his view, emotions do not contain intrinsic valence, such as positive or negative, although they are commonly labeled with valences generated from feelings. They "borrow" the labels that were originally developed as a component of homeostatic regulation (Damasio & Carvalho, 2013).

According to him, homeostatic feelings enable consciousness to the things that are co-experienced, thus overlaying the possibility of consciousness to whatever we taste, see, hear, or touch (Damasio, 2022). For instance, when we are hungry or in pain, we are instantaneously conscious of such situations, which is one of the factors why homeostatic feelings are so important (Damasio, 2022). To Damasio, consciousness starts with interoception and homeostatic feelings and goes up to high cognition. It is a bottom-up process.

Neuroscientist Anil Seth divides consciousness into several aspects. For him, "consciousness of the world" is the result of the brain operating as a prediction engine. Hence, perception is a process of informed guessing in an attempt to grasp what is around us: the brain makes its best guess by combining sensory data from the outside world with our prior expectations and beliefs about the world (Fig. 3). He states that our perception is fundamentally influenced by both external and internal factors (Seth, 2014, 2017).

He explains that the "consciousness of the self" shares similar reasoning based on predictions. He points out that there are numerous ways in which we can experience having a self, such as having and being a body (bodily self), perceiving the world from a first-person perspective (perspectival self), intending to do things and being the cause of things that happen in the world (volitional self), being a continuous and distinctive person over time (narrative self), built from a rich set of memories and social interactions (social self). These various ways in which we perceive being a self can split up; thus, being a unified self is a fragile construction of the brain (Seth, 2014, 2017, 2021).

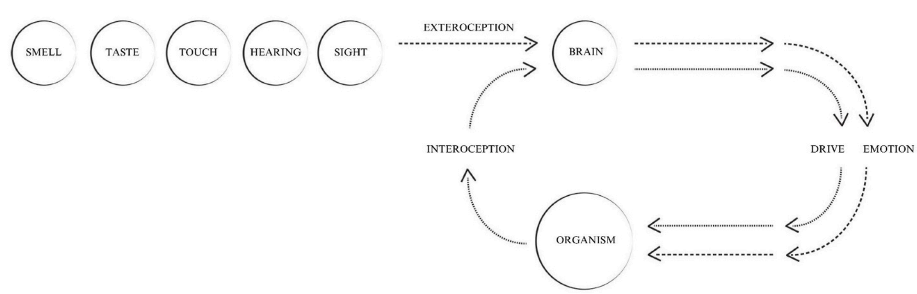

Fig. 2. Exteroceptive and interoceptive systems for Damasio.

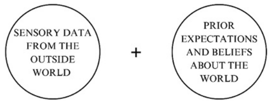

Fig. 3. Our consciousness of the world for Anil Seth.

Seth says that the same previous criteria apply to how the brain creates the experience of being and having a body (bodily self): the brain will try to guess what is and is not a part of the body. However, he points out that experiences outside of the body are fundamentally distinct from within. In the former, the brain creates predictions to figure out what is out there, and we perceive objects as the origins of sensations. In the latter, the brain uses predictions to control and regulate things, and we just experience how well or badly the control is working. He points out that we do not perceive each organ and its location; they are usually only felt when something goes wrong (Seth, 2014, 2017, 2021).

Consequently, a person's perception of the internal state of their body is about maintaining rigorous control over physiological aspects (homeostasis) consistent with survival. As a result, even our most fundamental feelings of being a self and an embodied organism are based on the biological processes that keep us alive. He explains that if we completely grasp this concept, we may see that all our conscious experiences start from this basic need to survive, as they all rely on the same predictive perceptual mechanisms. According to him, we experience ourselves and the world through the frame of, and because of, our living bodies (Seth, 2014, 2017, 2021).

Neuroscientist Lisa Barrett mentions that the brain constantly makes predictions about what will happen next. When this moment comes, it uses sensory input to either confirm or correct those predictions. This becomes our experience. She says that the brain predictively controls the systems inside the body, such as the cardiovascular, respiratory, and immune systems, among many others. The brain has to predict the needs of one's body and move the resources around so that the body gets what it requires before these needs arise, or else the person will be sick or hurt (Fig. 4). She exemplifies it by saying that if a person is going to stand up, the brain has to increase the blood pressure before doing so. Otherwise, the person will faint because there will not be enough oxygen reaching the brain (Barrett, 2018; Barrett & Simmons, 2015; Campbell, 2017).

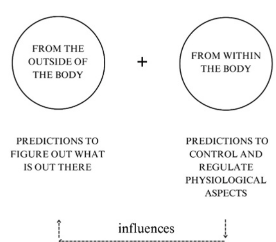

Fig. 4. Predictive perceptual mechanisms for Lisa Barrett.

She points out that emotions work the same way: what we feel is based on predictions from our knowledge and past experiences. According to her, how we feel alters what we see and hear. Moreover, we feel what our brains believe; therefore, believing is feeling. She suggests that we believe what we see, taste, smell, and hear.

She also suggests that we are not passive recipients of experience; we actively engage in selecting what we see, even though this occurs outside of our consciousness. Thus, the brain predictably regulates our body, influencing our sense's external inputs (Barrett, 2018; Barrett & Simmons, 2015; Campbell, 2017). For example, if our heartbeats increase, our also exteroception changes; hence we perceive things differently.

In essence, Damasio, Seth, and Barrett's works contribute to the idea that what one perceives or feels might start in one's body. They highlight the importance of the body in one's interactions with the physical world, and this article extends this concept to the virtual world. In addition, their works serve as basis to better understand the importance of bodily self-consciousness in the virtual world and to the notion that it is also based on predictions.

Consequently, while creating new virtual worlds, could designers pay greater attention to interoception, knowledge, and prior experiences and how they influence our perceptions, feelings and emotions?

4. Bodily self-consciousness enhanced by synchronous multisensory stimulation and interoceptive feedback

A widely known experiment in neuroscience, called the Rubber Hand Illusion (Fig. 5), explains how the experience of being and having a body works. While a person sits facing a desk without seeing one of their hands and looking at a false hand, a paintbrush is brushed on both hands: the real one, which is hidden, and the false one, which is visible. As a result, most people slowly believe that the false hand is a genuine part of their body (Botvinick & Cohen, 1998; Craig, 2003; Seth, 2017; Suzuki et al., 2013).

This experiment shows that if the brain sees and feels touch on an object that resembles a hand and is about where it should be, it may infer that the false hand is a part of the body. Therefore it is clear that, even the perception of one's body is a type of guesswork by the brain, and that identifying with a body relies on having a conscious self. It also shows how individual variations in sensitivity to internal body signals (interoception) influence the degree of this modulation, as well as how the timing of exteroceptive, visual and tactile body-related feedback may be utilized to alter the sensation of body ownership. Thus, for the brain to perceive the body as its own, it needs to integrate information from touch, vision, and proprioception in a way that makes sense over time, and this integration is influenced by how these different senses relate to

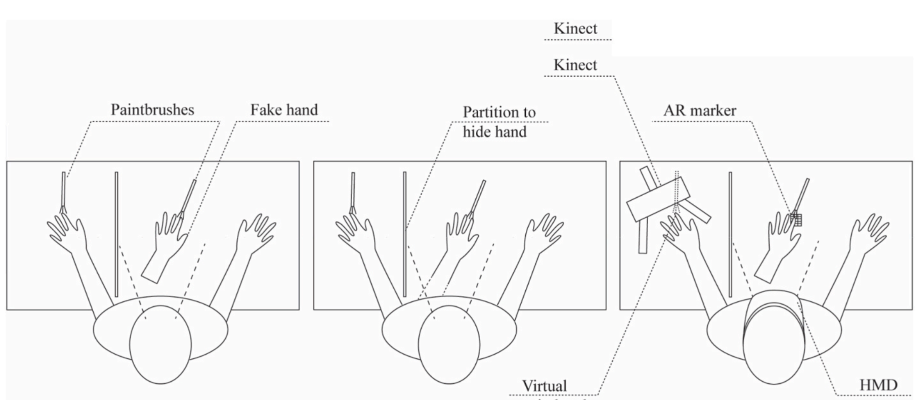

Fig. 5. First two images: Rubber Hand Illusion setup, and the third: Rubber Hand Illusion in virtual reality setup.

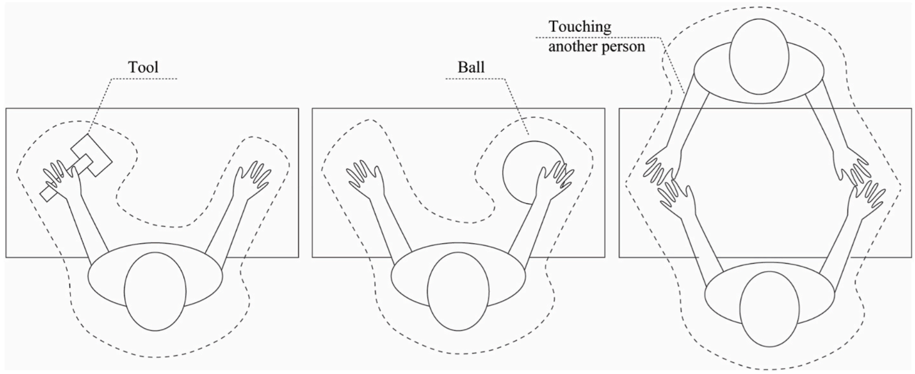

Fig. 6. Peripersonal space expansion.

each other (Botvinick & Cohen, 1998; Seth, 2017; Suzuki et al., 2013).

Anil Seth and his colleagues at the University of Sussex have developed a new version of the Rubber Hand Illusion (Fig. 5), in which people sat facing a desk so they couldn't see their hands. A virtual hand was projected on the head-mounted display (HMD) at the location of the AR marker, which was built in real-time using a 3D model of the actual hand obtained by the Kinect. The virtual hand was superimposed over people's front-facing cameras linked to the HMD (Seth, 2017; Suzuki et al., 2013).

In addition, people wore pulse oximeters in their left hand to monitor the timing of their heartbeats. Cardio-visual feedback was accomplished by shifting the color of the virtual hand from its natural color to red and back again in 500-ms intervals, either synchronously or asynchronously, with the heartbeat. A paintbrush was created in the AR environment to provide tactile feedback. A customized proprioceptive drift test for the AR environment was used to determine the objective measurements of virtual hand ownership, utilizing a virtual measure and cursor whose scale and placement matched the ones in the real world (Seth, 2017; Suzuki et al., 2013).

When the hand flashes synchronously—at the same rate as their heartbeat—people were more convinced that the virtual hand was part of their body. This experiment shows how the perceptions of our internal state and regulating mechanisms contribute to our sensation of having a body. According to Anil Seth, "We predict ourselves into existence" (Seth, 2017).

Other experiments also present how synchronous visuo-tactile stimulation can increase self-identification, but with another person's face (Sforza et al., 2010; Tsakiris, 2008), a virtual body — the Full Body Illusion (Lenggenhager et al., 2007) or someone else's body (Ehrsson, 2007; Petkova & Ehrsson, 2008; Suzuki et al., 2013). For example, during the Full Body Illusion, participants see a virtual body (avatar) located 2m in front of them, being stroked while synchronously receiving a congruent tactile stimulation on their physical body. In such cases, participants report identifying with the virtual body and feeling displaced toward the virtual body (Lenggenhager et al., 2007; Noel et al., 2015). These studies demonstrate how crucial exteroceptive inputs are in developing multisensory integrated self-models.

Regarding interoceptive inputs, some studies highlight their importance and the sense of one's body's internal physiological state in supporting one's sense of self (Craig, 2009; Critchley et al., 2004; Damasio, 2010; Seth et al., 2012; Suzuki et al., 2013).

Both of these ideas combine to form the main concept of Seth's Rubber Hand Illusion: that selfhood arises through the development of interoceptive representations and their integration with exteroceptive signals (Suzuki et al., 2013).

Therefore, a crucial aspect of our sense of self as a subject of conscious experience is the experience of the bodily self, which is the feeling of being within a body we own and control (Blanke & Thomas, 2009; Gallagher, 2005; Jeannerod, 2006). Experimental studies show that the sense of owning a body (self-identification) and being located within the boundaries of that body (self-location) are fundamentally rooted in the harmonious and coherent integration of multiple sensory modalities within the spatio-temporal aspects of the physical body (Blanke, 2012). Indeed, changing the spatio-temporal congruency of several sensory modalities can produce a variety of physiological illusions, like the Rubber Hand, the Full Body, and Out-of-Body illusions (Noel et al., 2015).

In conclusion, all these experiments redefine the perception of what is or is not part of our body. They also demonstrate how exteroceptive and interoceptive data can be used to enhance bodily self-consciousness. They raise questions about how designers may use a combination of synchronous multisensory stimulation and interoceptive feedback, such as heartbeat, in order to enhance the relationship between the physical and the virtual world. This is especially relevant in the era of biofeedback, wearable technologies, and Quantified Self practices, all of which can provide insight into interoception (Macruz et al., 2022).

5. Peripersonal space as part of the space of the bodily self

Every person has a "map" in their brain that tells them how the body is organized according to structure, function, location, and size. One of the basic maps the brain keeps is an entire map of the surface of our body. The ongoing sensory feedback from our body significantly influences our sense of self (Blakeslee & Blakeslee, 2008; Campbell, 2007).

For example, the experiments of the Rubber Hand Illusions reveal how important it is the fit between our internal maps and sensory data to the sense of who we are. If the position of the fake hand aligns with the placement of someone's own hand, they may perceive the fake hand as a part of themselves. Nonetheless, if the alignment is incorrect or off, someone does not assume that the hand belongs to them (Campbell, 2007; Blakeslee & Blakeslee, 2008; Rizzolatti et al., 1997).

According to neuroscientist Giacomo Rizzolatti, it was only recently discovered that monkey and human brains include maps of our bodies and the area surrounding them, known as peripersonal space (Rizzolatti et al., 1997; Rizzolatti & Fabbri-Destro, 2010). The capacity to utilize tools is a direct outcome of having a map of this area around us as if they almost blend in with us. Examples include eating with a knife and fork, driving a car, or playing a game in which a ball or a racket feels as if they constitute one entity with us (Fig. 6) (Campbell, 2007, 2008).

The maps of our peripersonal space are constantly altering as the things we engage with in our surroundings change (Rizzolatti et al., 1997; Rizzolatti & Fabbri-Destro, 2010). They also respond to other individuals; these spatial maps have distinct comfort zones in different cultures (Campbell, 2007).

Peripersonal space is why we may become so caught up in virtual worlds such as video games and other virtual activities (Campbell, 2007). It can expand if someone begins arranging the space or using a tool, such as a cane. In this condition, they are touching the cane while

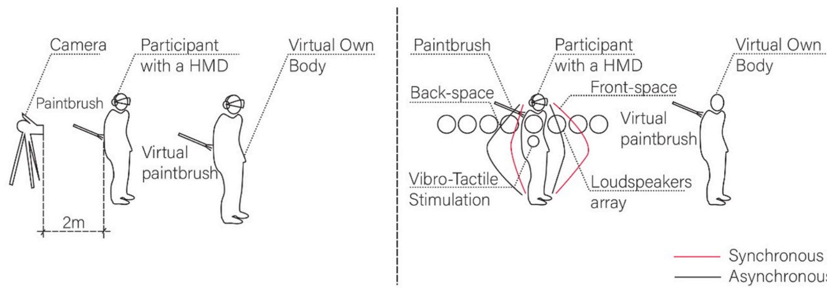

Fig. 7. First image: Full Body Illusion setup, and the second: Full Body Illusion and peripersonal space setup.

also feeling contact with the floor (DigitalFUTURES, 2021).

It has already been suggested that during the Full Body Illusion (Fig. 7), synchronous tactile stimulation on the body of the participants, together with visual stimulation from the avatar seen at an extracorporeal location, may broaden the visual and receptive fields of neurons that code for peripersonal space (Blanke, 2012). Multisensory peripersonal space neurons integrate visual, tactile, and auditory stimuli when presented at a limited distance from the body (Bremmer et al., 2002; Graziano & Cooke, 2006; Makin et al., 2008; Petkova et al., 2011; Rizzolatti et al., 1997). This limit determines the border of peripersonal space, which is also called plastic, as the space where multisensory stimuli are integrated expands when people engage with different tools (Làdavas & Serino, 2008; Maravita & Iriki, 2004; Noel et al., 2015; Serino et al., 2015).

An experiment was done to better understand peripersonal space in the Full Body Illusion, in which a participant viewed on a head-mounted display (HMD) a virtual body in front of them. Tactile stroking was applied to the participant's back, while synchronous or asynchronous visual stroking was seen on the virtual body's back. Peripersonal space representation was tested by measuring response times to vibrotactile stimuli applied to the individual's chest while task-irrelevant looming noises were provided from a loudspeaker array situated alongside the participant. During synchronous stroking, or when the Full Body Illusion is generated, the peripersonal space representation expands toward the virtual body in front-space (boundary of peripersonal space initially between 60 and 75 cm and enlarged to 75–90 cm —red line in the figure) while simultaneously contracting in back-space (initially 75–90 cm away and shrunk to 60–75 cm—black line in the figure) (Fig. 7) (Noel et al., 2015).

The experiment findings support the theory that during the Full Body Illusion, peripersonal space boundaries translate toward the virtual body, causing peripersonal space representation to shift from being centered at the physical body's location to being centered on the subjectively experienced location of the self (Noel et al., 2015).

In conclusion, understanding body maps and peripersonal space allows us to discuss the idea of an extended body as a dynamic system that connects our physical body to other bodies across the physical and the virtual worlds. This reinforces the concept that the body is growing further detached from us while being more connected than ever. It also raises questions about how to use integrated visual, tactile, and auditory stimuli to expand peripersonal space when presented at a limited distance from the body.

6. Bodily self-consciousness and the creation of new virtual worlds: discussion

The neuroscientific works and experiments shown in the article emphasize the importance of the body's internal processes and the environment in which this organism operates, as both of them are required for regulation (homeostasis) (Carvalho & Damasio, 2021; Damasio, 2005; Parvizi & Damasio, 2001). They raise questions about the beginning and end of the body and place the environment as an extension of it. This allows us to draw a parallel between the body, including peripersonal space (Rizzolatti et al., 1997; Rizzolatti & Fabbri-Destro, 2010), and the Autopoiesis Theory. This theory was proposed by neuroscientists Varela and Maturana and suggests that systems continuously construct themselves and define their own relations to the environment (Maturana & Varela, 1980). In this scenario, one input from the body's interior changes an external input, which changes additional input from within, and so on.

Therefore, if systems are never static, can virtual worlds become more interactive, fostering heightened consciousness of individuals' impact of their behavior on the environment? Might this real-time feedback loop between user behavior and design shape how new virtual worlds are built?

Some works are moving in this direction, showing a more porous relationship between body and mind, physical and virtual, interoception and exteroception, humans and machines. One of these works is that of The Tangible Media group at MIT, which has created a wrist-worn mobile heart rate regulator device. It uses tactile stimulation to provide closed-loop biofeedback to users depending on their heartbeat rate. The device uses physiological synchronization through a touch mechanism to smoothly regulate heart rate, which is closely related to mental stress levels. Therefore, tactile stimulation guides the user's heart rate to resonate with the device in order to either raise or drop the heart rate with the least amount of cognitive load (Choi and Ishii, 2020).

The same lab has developed a portable pneumatic-haptic device that uses subtle tactile feedback to assist users in regulating their breathing rate. The tactile stimulation patterns, intensity, and frequency can be personalized using a variety of air pouch actuators, which may individually inflate and deflate. The device helps people reduce their average breathing rate while keeping a high level of pleasantness and energy (Choi, 2020, 2022).

Another work from MIT Media Lab explores the relationship between physiology, affective display and internal cognitive calibration. A subliminal physiological stress signal of the body (goosebumps) was enhanced and transferred to an artificial skin that displayed this physiological and emotional output (goosebumps). This output was associated with a galvanic skin response (sweaty palms) to see whether it could positively influence behavioral changes (Liu, n.d.). Even though the results of this work are inconclusive, they were extremely important because they show how interoception influences exteroception and vice-versa.

However, despite the fact that all these works contain virtual elements, they are still mainly focused on the physical world. The challenge would be how they could add to virtual world and create a feedback loop between interoception, proprioception and exteroception.

One area that blurs the line between physical and virtual worlds is interface design. Cell phones usually collect data about our activities and other information. Nevertheless, we do not know what information is being collected and used to improve the device interface and user experience. Similarly, computers, social media, and AIs, like ChatGPT, constantly extract data about us, such as facial recognition, eye gaze, motion analysis, and personal background and preferences. This

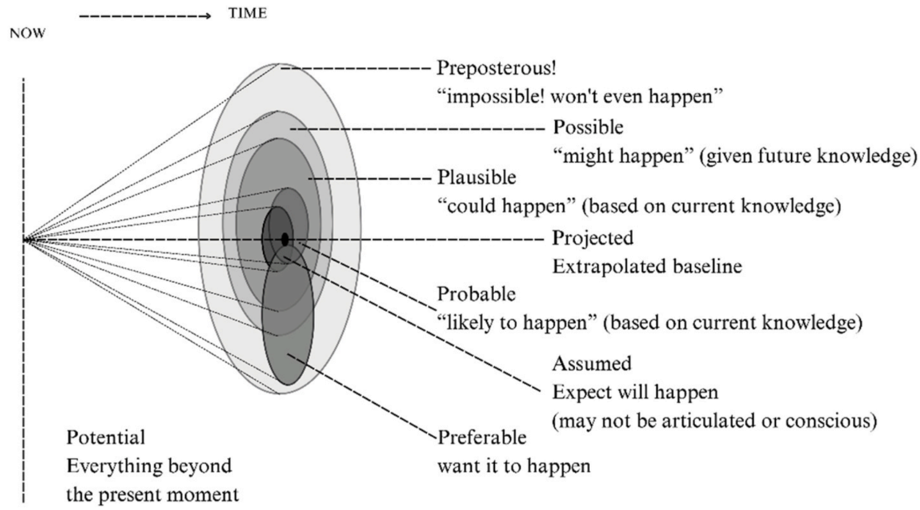

Fig. 8. The "Futures Cone" diagram setup, based on Joseph Voros' 2017.

information is rarely used in a transparent, conscious, and valuable manner to provide us with meaningful insights about ourselves. The challenge might be how to use this collected data to improve our perception of ourselves, others, and the environment—understanding them as an extension of ourselves. Hence, deeper connections between the physical and the virtual worlds could emerge.

This article opens new doors for the design of "Future Possibilities" rather than limiting itself to a specific design proposal. Considering Joseph Voros's Futures Cone diagram (Voros, 2017), these future possibilities might include projects in a range from Preferable to Possible Futures (Fig. 8). Preferable Futures are those that "should" or "ought to" happen according to normative value judgments. Possible futures are those that might happen, given future knowledge. Between these two, other types of Futures are included and should also be considered. As a result, many design possibilities with distinct degrees of immediate practicality and feasibility may be embraced.

7. Conclusion

The research is carried out through multiple directions. The first proposed direction to increase bodily self-consciousness is the use of synchronous multisensory stimulation. This article specifically explored the combination of visuo-tactile inputs, but designers could explore other combinations in virtual worlds, furthering our knowledge and application in this field.

The second is the use of synchronous interoceptive feedback. The research suggests that designers can create more inclusive and performative virtual worlds by accommodating variations in sensory and motor abilities. This can be applied in assisting people experiencing anxiety or cognitive challenges or with temporary disabilities as it can contribute to self-consciousness and the regulation of the internal state of users. This also can be applied to detect muscular tension, providing users with guidance on techniques to promote stress reduction and relaxation.

The third involves the use of peripersonal space expansion. Peripersonal space also appears to be one of the integrated elements that support our feeling of physical self-awareness, which in turn supports our entire sense of self. As peripersonal space representation shifts from being centered on the physical body toward the virtual one, it raises questions such as how using peripersonal space in virtual worlds provides people with more control over the space surrounding them. One avenue of exploration lies in the development of tools that allow users to tailor the size and positioning of the virtual world in relation to their own body and peripersonal space, thereby engendering a more personalized and user-centric experience. Another conceivable application involves the integration of avatars within the virtual world, calibrated to convey social cues, such as eye contact or proximity, adapted to the individual's peripersonal space.

The fourth combines these three directions: synchronous multisensory stimulation, interoceptive feedback, and peripersonal space expansion. Deeper work is necessary on this path, as neuroscientific literature increasingly draws attention to the interdependence of these factors. The dynamic interplay between the stimulation of different sensory inputs, interoceptive technologies, and the plasticity of peripersonal space may yield novel opportunities for increasing bodily self-consciousness and redefining the perception of spatial boundaries within the virtual world (Summary of the main directions, see Table 1).

One limitation of this research is that individual variations in sensitivity to internal body signals influence the degree of this modulation and the timing of exteroceptive, visual, and tactile body-related feedback that alters the sensation of body ownership. Thus, current models of how this works can be enriched with a temporal dimension of synchronous interoceptive feedback, multisensory stimulation, and peripersonal space expansion. For this, designers could work with neuroscientists to test different stimuli and their timing in distinct settings.

Another limitation is that as much as these four directions can be integrated into the design of different types of virtual worlds, each technique might be better for a specific type, and this would need to be tested to be better understood. It would be particularly important to do tests in virtual worlds where bodily self-consciousness is more emphasized, like in those with higher levels of local presence and telepresence, such as augmented or diminished mixed realities, and holistic virtual reality.

In general, the research proposes a theoretical research method for enhancing bodily self-consciousness in the virtual world. Although it lacks experimental validation as a narrative review, it also lays the groundwork for future practical experiments.

Table 1
Summary of the main directions.

Directions	Main concepts	Implemented through
Direction 01	synchronous multisensory stimulation	visuo-tactile stroking
Direction 02	synchronous interoceptive feedback	visual cardiac biofeedback, breathing patterns, others …
Direction 03	peripersonal space expansion	visuo-tactile stroking, audio–tactile interaction
Direction 04	combination of the above	

CRediT authorship contribution statement

Andrea Macruz: Writing – original draft, Conceptualization, Methodology. **Bing Zhao:** Writing – review & editing, Methodology. **David Sperling:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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