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# The Sense of Embodiment in Virtual Reality

## Abstract

What does it feel like to own, to control, and to be inside a body? The multidimensional nature of this experience together with the continuous presence of one's biological body, render both theoretical and experimental approaches problematic. Nevertheless, exploitation of immersive virtual reality has allowed a reframing of this question to whether it is possible to experience the same sensations towards a virtual body inside an immersive virtual environment as toward the biological body, and if so, to what extent. The current paper addresses these issues by referring to the Sense of Embodiment (SoE). Due to the conceptual confusion around this sense, we provide a working definition which states that SoE consists of three subcomponents: the sense of self-location, the sense of agency, and the sense of body ownership. Under this proposed structure, measures and experimental manipulations reported in the literature are reviewed and related challenges are outlined. Finally, future experimental studies are proposed to overcome those challenges, toward deepening the concept of SoE and enhancing it in virtual applications.

## 1 Introduction

One of the central questions in cognitive science is how we experience ourselves inside a body that interacts continuously with the environment. We experience our self as being inside a body and more specifically a body that feels "ours," which moves according to our intentions, obeying our will. In everyday life, these sensations are normally coupled together, perceived as emerging from only one body, the biological one, giving coherence to our self and our body representation.

Experimental manipulation of this embodied experience is problematic, since one's body is always present and seemingly cannot be dissociated from one's self. However, studies of body perception reveal an alternative way to approach this experience by manipulating the identity of a body part. In a now classical experiment, the participant sits comfortably at a table with his or her left hand resting on it. A left rubber hand is put on a table aligned with and close to the real one. An occluding screen prevents the sight of the real left hand and arm. Both the rubber hand and corresponding real hand receive synchronous tactile stimulation from two paintbrushes at the same relative positions. After a few seconds of such synchronous stimulation, the participant will probably experience a profound illusion known as the rubber hand illusion (RHI)—the rubber

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hand feels as if it were his or her real hand (Botvinick & Cohen, 1998). Additionally, when asked to indicate where the real hand is located, with eyes closed, the participant will typically mislocalize it toward the rubber hand in comparison to a similar measurement taken before the synchronous visual-tactile stimulation (Botvinick & Cohen; Costantini & Haggard, 2007; Tsakiris & Haggard, 2005). The difference between the pre and post experimental position estimation is widely considered a perceptual correlate of the illusion and is known as proprioceptive drift. Furthermore, asynchronous stimulation of the real and rubber hand has been shown to inhibit both the illusion and the mislocalization (Armel & Ramachandran, 2003; Botvinick & Cohen; Tsakiris, Carpenter, James, & Fotopoulou, 2010).

Although the RHI has provided an easy and replicable way to address the identity of a body part, revealing at the same time the role of multimodal input in the embodied experience, the question of how we experience ourselves inside a body could not be addressed in its entire complexity due to the experiment limitations. The employment of virtual reality (VR) can be used to reframe the main research question to address instead: How, and to what extent, can we experience a virtual body representation as our own body within a virtual environment (Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2009)? Such use of virtual reality techniques is encouraged by its unique advantages to easily manipulate the perceived scenario, but more importantly to vary in a controlled way factors associated with the embodied experience that would hardly be possible in physical reality (Bohil, Alicea, & Biocca, 2011). For example, VR makes possible in a relatively easy manner the manipulation of the body representation in terms of structure, morphology, and size, dissociating the egocentric visual perspective from the body, and exploiting the role of multimodal information in spatiotemporal terms for body perception. Indeed, recent studies using VR or similar techniques have made the first steps to approach the multidimensionality of the embodied experience by inducing whole body illusions analogous to the RHI (Normand, Giannopoulos, Spanlang, & Slater, 2011; Petkova & Ehrsson, 2008; Slater, Spanlang, Sanchez-Vives, & Blanke, 2010).

The current paper presents a review and elucidation of the concepts and mechanisms involved in these types of illusions 5 by focusing on the phenomenology of *embodiment*. The term *embodiment*, however, has been referred to differently in various contexts due to its multidisciplinary use and its various application areas, and for this reason its conceptualization depends on the viewpoint from which the issue is considered. From the philosophical perspective it is a part of the general discussion on how one defines and experiences one's self (Blanke & Metzinger, 2009; Metzinger, 2008). For cognitive neuroscience and psychology, it is concerned with the question of how the brain represents the body (Berlucchi & Aglioti, 1997; Graziano & Botvinick, 2002) and how this representation is altered under certain neurological conditions (Lenggenhager, Smith, & Blanke, 2006; Metzinger, 2009). In contrast, in robotics, the concept is employed to distinguish ways through which artificial forms of intelligence are represented contrasting those virtual agents and robots that have a real physical representation compared to those that do not (Foster, 2007; Holz, Dragone, & O'Hare, 2009; Wainer, Feil-Seifer, Shell, & Mataric, 2006). Embodiment has been also discussed in relation to presence in virtual environments (Biocca, 1997), especially as there is evidence to suggest that a virtual body in the context of a head-mounted display based virtual reality is a critical contributor to the sense of being in the virtual location (Slater, Spanlang, & Corominas, 2010). Furthermore, the role of embodiment in one's self-representation was also addressed under the concept of self-presence introduced by Biocca and restated further by Lee (2004).

The existence of multiple meanings of the term *embodiment* can cause confusion in the research community of the same type that has dogged the study of presence (Lee, 2004). For this reason, throughout the rest of the paper, the term *Sense of Embodiment*[1] (SoE) will be used to refer to the ensemble of sensations that arise in conjunction with being inside, having, and controlling

1. For a conceptual differentiation between embodiment and sense of embodiment see de Vignemont (2011).

a body[2] especially in relation to virtual reality applications. The aim of the present paper is to provide a working definition for SoE, to discuss the corresponding measures used in the literature and propose new ones, and finally to review factors that potentially enhance the SoE in VR, relating to existing experimental studies. Research questions for future studies in the context of SoE are pointed out aiming toward a deeper understanding of this complex and multidimensional experience.

## 2 Sense of Embodiment (SoE)

### 2.1 Working Definition

Understanding and defining the SoE toward an artificial body can draw on ideas from recent proposals concerned with the embodiment of artificial body parts (i.e., specific limbs), by extending these ideas to artificial whole bodies. According to de Vignemont (2011, p. 3), an object "E is embodied if and only if some properties of E are processed in the same way as the properties of one's body." This definition is in line with that of Blanke and Metzinger (2009, p. 7) who state that embodiment includes the "subjective experience of using and 'having' a body." Therefore, the following definition is adopted:

> SoE toward a body B is the sense that emerges when B's properties are processed as if they were the properties of one's own biological body. (Definition: D)

### 2.2 Underlying Structure

Defining SoE in this manner, the conceptual clarification still remains vague, because the properties and the associated experiences from one's biological body are not specified further. Nevertheless, everyday experience concerning the biological body can manifest itself in at least three main classes of such properties with the corresponding phenomenology. First, one's self-representation in a body is driven and highly characterized by its spatial attributes; for example, one's self is located inside a body. Furthermore, this spatial representation is always self-attributed; that is, the body where one perceives one's self is one's own body. Finally, this body also obeys the intentions of one's self; for example, one is the author of one's body's actions. Indeed, in reviewing the literature, the term *embodiment* has frequently been associated with the concepts of *sense of self-location* (e.g., Arzy, Thut, Mohr, Michel, & Blanke, 2006), the *sense of agency* (e.g., Newport, Pearce, & Preston, 2010) and the *sense of body ownership* (e.g., Lopez, Halje, & Blanke, 2008). Therefore, the properties of one's biological body could be described under the conceptual umbrella of these three terms.

#### 2.2.1 Sense of Self-Location.

Self-location is a determinate volume in space where one feels to be located. Normally self-location and body-space coincide in the sense that one feels self-located inside a physical body (Lenggenhager, Mouthon, & Blanke, 2009). However, this collocation can break down when people have out-of-body experiences (OBE) in which they perceive themselves outside of their physical body (Lenggenhager et al., 2006).

The sense of self-location refers to one's spatial experience of being inside a body and it does not refer to the spatial experience of being inside a world (with or without a body); for example, the experience of presence—specifically, Place illusion (Slater, 2009) or the sense of "being there." Self-location and presence are psychological states that refer to different issues. Whereas self-location is concerned with the relationship between one's self and one's body, presence refers to the relationship between one's self and the environment. If there is a body representation where the self is perceived to be, then the latter issue also includes the issue of the relationship between the body and environment. To better illustrate this distinction between self-body and self-environment or body-environment, an example of self-location could be the feeling that one's self is located inside the biological body or an avatar's body; whereas the analogous feeling for presence would be the feeling of one's self being located in a physical or virtual room, even if this does not require a body representation in the form of an avatar. By considering a dichotomy of space

2. In this paper, we will make use of the term "body" as a container, which can be any object in the context of virtual reality, and we will make a special distinction when we refer to one's biological body.

between the self-body space (the space occupied by the body B in which the self is perceived as located) and the external/environmental space (the space-environment-world where the self is perceived as situated even if this does not include a body). The view makes the distinction become more clear. A more extended approach to embodiment could potentially include the presence subcomponent; however, here we focus on the relationship between self and body. Although self-location and presence address different spatial questions, they can be considered as complementary concepts that together constitute one's spatial representation.

Self-location is highly determined by the visuospatial perspective given that this is normally egocentric. Indeed, it has been shown that where one feels located can be influenced by the origin of visuospatial perspective (Blanke & Metzinger, 2009; Ehrsson, 2007). Other studies on the role of perspective (e.g., Petkova, Khoshnevis, & Ehrsson, 2011; Slater, Spanlang, Sanchez-Vives, et al., 2010), showed that physiological responses to a threat given to an artificial body were greater for first-person perspective than for third-person perspective. The importance of egocentric visual perspective for self-location was also highlighted by Lee (2004, p. 40) referring to self-presence: "In the case of a psychologically assumed virtual self (. . .) a virtual environment reacts to users as if they were in there (e.g., first-person viewpoint game, other people greeting you by name)." Although the present paper is concerned with highly immersive virtual reality systems, the statement is in line with the proposed subcomponent, since first-person perspective given from the position of the virtual body serves as sensory evidence toward one's self-localization inside the virtual body.

Vestibular signals are also considered to play a significant role in one's self-localization (Lopez et al., 2008). These signals contain information with respect to the "translation and rotation of the body in addition to orientation with respect to gravity" (Blanke & Metzinger, 2009, p. 10). Interestingly, vestibular dysfunction was observed in patients with OBE who experience themselves inside an illusory body while the origin of visual perspective is perceived as coming from a position outside the bodily boundaries (Blanke, Landis, Spinelli, & Seeck, 2004).

The tactile input also influences self-location since the border between our body and the environment is our skin. This is also related to the brain's different encoding of the space dependent on its proximity to the body. According to this criterion, personal space is the space our body occupies, peripersonal space is the space adjacent to the body that is within arms' reach, and extrapersonal space is the far nonreachable space (Halligan, Fink, Marshall, & Vallar, 2003; Vaishnavi, Calhoun, & Chatterjee, 2001). Relevant to this is the extension of peripersonal space by tool use that results in tool embodiment (Giummarra, Gibson, Georgiou-Karistianis, & Bradshaw, 2008). In addition, self-localization inside a body with a different volume compared to one's biological body's, results in a differently perceived personal space as addressed in the study of Normand et al. (2011). The study of Lenggenhager et al. (2009) revealed that the position of seen tactile stimulation when accompanied by congruent physical stimulation can dominate the visual perspective and thus determine our self-location.

**2.2.2 Sense of Agency.** The sense of agency refers to the sense of having "global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will" (Blanke & Metzinger, 2009, p. 7). Agency is present in active movements. An example where agency is disturbed is in patients with anarchic hand syndrome, who reject the notion that they are controlling the actions of their own limb and claim that their limb acts according to its own intentions (David, Newen, & Vogeley, 2008).

The sense of agency has been proposed to result from a comparison between the predicted sensory consequences of one's actions from the efference copy and the actual sensory consequences (for a review see, e.g., David et al., 2008). When the predicted consequences of the action and the actual consequences of actions match by, for example, the presence of synchronous visuomotor correlations under active movement, one feels oneself to be the agent of those actions. This also applies for the embodiment of tools when these are under the control of the user. The development of agency depends on the synchronicity of visuomotor correlations. Several studies have shown that discrepancies between the visual feedback of the action and the actual movement negatively affect the feeling of agency (Blakemore, Wolpert, & Frith, 2002; Franck et al., 2001; Sato & Yasuda, 2005). In the study of Franck et al., a discrepancy of more than 150 ms was found to reduce agency.

**2.2.3 Sense of Body Ownership.** Body ownership refers to one's self-attribution of a body (Gallagher, 2000; Tsakiris, Prabhu, & Haggard, 2006). It has a possessive character and it implies that the body is the source of the experienced sensations. For example body ownership is disturbed in patients with somatoparaphrenia who deny the ownership of their limb (Vallar & Ronchi, 2009).

The sense of body ownership has been proposed to emerge from a combination of bottom-up and top-down influences (Tsakiris, 2010; Tsakiris & Haggard, 2005). Here, bottom-up information refers to the afferent sensory information that arrives to our brain from our sensory organs; for example, visual, tactile, and proprioceptive input, whereas top-down information consists of the cognitive processes that may modulate the processing of sensory stimuli; for example, the existence of sufficient human likeness to presume that an artificial body can be one's body.

In terms of bottom-up influences, several studies on the RHI have investigated the role of the synchronous visuotactile correlations between the real and the rubber hand. For the RHI, illusory ownership of the rubber hand emerges only when the seen and the felt stimulation follow the same spatiotemporal pattern (Botvinick & Cohen, 1998; Shimada, Fukuda, & Hiraki, 2009; Tsakiris & Haggard, 2005). Analogous to visuotactile correlations, synchronous visuoproprioceptive correlations during passive movements were also found to induce ownership (Dummer, Picot-Annand, Neal, & Moore, 2009; Tsakiris, Prabhu, & Haggard, 2006).

Other studies have focused more on the cognitive influences in the induction of the illusion and have revealed that the strength of body ownership depends on the degree of morphological similarity between a real biological arm or hand and the external object to be incorporated (Armel & Ramachandran, 2003; Ehrsson, Spence, & Passingham, 2004; Tsakiris et al., 2010; Tsakiris, Costantini, & Haggard, 2008; Tsakiris & Haggard, 2005) or the similarity of spatial configuration between them (Costantini & Haggard, 2007; Ehrsson et al.; Tsakiris & Haggard). These studies showed that the illusion of ownership diminishes when the external object does not resemble or is in a different spatial configuration to the real arm or hand. However, in line with these top-down influences, several studies have shown that the illusion of ownership of a fake hand can be induced when there is morphological similarity to a real hand and arm; for example, rubber arm and hand (Botvinick & Cohen, 1998), screen images of the real hands (IJsselsteijn, de Kort, & Haans, 2006; Tsakiris et al., 2006), other people's hands (Schutz-Bosbach, Mancini, Aglioti, & Haggard, 2006), or virtual hands (Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008). These two together imply that in order to induce ownership toward an external object, a basic morphological similarity with the real body part is needed.

Recently, it has been shown that body ownership is not exclusive to artificial body parts but can also be felt for artificial whole bodies; for example, avatars or mannequins (Normand et al., 2011; Petkova & Ehrsson, 2008; Slater et al., 2009; Slater, Spanlang, Sanchez-Vives, et al., 2010).

The concept of SoE is regarded as having these three underlying subcomponents: self-location, agency, and body ownership. Evidence in favor of such a structure was recently presented in the study of Longo, Schüür, Kammers, Tsakiris, and Haggard (2008) investigating SoE in the RHI. A principal component analysis of the results of a set of questionnaire items revealed that the phenomenology of embodiment breaks down into these three proposed subcomponents. However, there are some limitations in the interpretation of these results; for example, only the presumed agency was measured (there was no actual agency for the rubber hand) and the induced embodiment was for an artificial body part and not for an artificial whole body. Despite these constraints, the analysis of Longo et al. revealed that the

**Table 1.** *Propositions for SoE Toward a Body B*

| | |
|---|---|
| One experiences SoE toward a body B, | if one feels *self-located* inside B at least in a minimal intensity (P1) |
| | if one feels to be an *agent* of B at least in a minimal intensity (P2) |
| | if one feels B as one's *own* body at least in a minimal intensity (P3) |
| | if and only if one experiences at least one of the three senses at least in a minimal intensity (P4) |
| One experiences full SoE toward a body B, | if one experiences all of the three senses at the maximum intensity (P5) |

phenomenology of embodiment includes the sense of self-location, interpreted there as body part location, the sense of agency, and the sense of body ownership.

### 2.3 The Scale of the SoE

Under normal conditions, these three senses are always experienced and without any doubt with respect to the biological body. Nevertheless, in experimental manipulations of these senses, such as in the RHI, participants are required to express their illusory sensations on a continuous scale (Botvinick & Cohen, 1998) rather than a two-valued/binary/forced choice one; for example, "I felt versus I didn't." The possible variance in the intensity of ownership feelings toward the rubber hand would imply that sense of ownership is on a continuous scale, although in normal life such in-between values are never considered. (Of course, the continuous scale—or the ordinal scale typically employed in questionnaires—is actually only a measuring device used by experimenters and we cannot assume from this that the underlying phenomenon is itself experienced on a continuous scale.) This continuous scale has been applied for the sense of self-location (Ehrsson, 2007) and agency (Longo et al., 2008). Therefore, in this framework, the intensity of experiencing the three subcomponents could be considered to vary continuously from none to a maximum degree. The fact that SoE is considered as the synthesis of these three senses, implies that SoE is also expressed on a continuous scale from no to full degree, as also stated by de Vignemont (2011). In the special case of one's biological body, all senses are experienced in the maximum degree and one feels fully embodied.

### 2.4 Propositions of the SoE

Given the definition D and the proposed scale for SoE, the following propositions (P) can be derived as shown in Table 1.

From Table 1, P5 is true for one's biological body but it remains unknown whether such full embodiment can be induced toward an artificial one. Minimal intensity and maximum intensity here refer to the possible strength of the induced sense(s). These values depend both on the evidence toward the sense(s) that the specific experiment provides to participants; and on the participants' perceptual mechanisms.

### 2.5 Relationship Between SoE and its Subcomponents

Having conceptualized the SoE as consisting of these three subcomponents, evidence in favor of a dominant component or information related to each subcomponent's contribution to the overall concept would serve both future experimental manipulations of SoE as well as theory. Nevertheless, the literature does not provide either enough information or converging information toward one single interpretation. Concerning self-location, some authors treat embodiment as synonymous to this (Arzy et al., 2006; Blanke & Metzinger, 2009; Lenggenhager, Tadi, Metzinger, & Blanke, 2007), which could further imply that self-location is the dominant subcomponent in SoE or just a sufficient condition (P1). On the other hand, body ownership has been proposed to be unnecessary, an argument motivated by tool embodiment (De Preester & Tsakiris, 2009) which does not manifest feelings of body ownership (de Vignemont, 2011), also consistent with P4. Furthermore, perceived agency has been proposed to be an important factor which gives coherence to one's body representation (Tsakiris et al., 2006), consistent with P2. Moreover, perceived lack of agency was shown to inhibit embodiment (Newport et al., 2010). Even though these approaches to the concept of embodiment do not include all the proposed subcomponents, they are not in conflict with the proposed definition and propositions. On the contrary, they can be considered to focus on a subset of sensations associated with particular subcomponents and not to the entire complexity of the SoE experience.

The current state of knowledge in literature on SoE does not enable further specification concerning the weights of the three subcomponents in the totality of the embodied experience. These weights may not be constant but time-varying (e.g., related to participants' perceptual and attentional mechanisms), or experiment-specific (e.g., related to the provided sensory information that the particular scenario offers, especially for each sense or for the task that participants are asked to do). Furthermore, there is not enough systematic experimental evidence in favor of independence of the three subcomponents.

Probable dependencies or correlations between the subcomponents have been suggested in the literature. First, concerning the relationship between self-location and body ownership, a body inside which one feels self-located is very likely to be one's own body. In the study of Petkova et al. (2011) the visual perspective (related to one's self-location) was found to affect the induced body ownership. The main research question, however, was about body ownership and not about self-location. Hence, it remains unclear whether visual perspective is necessary for body ownership or whether breaking the self-location weakened the induced body ownership. Secondly and similarly, a correlation between agency and body-ownership can exist; for example, a body that obeys one's intentions will probably be one's body and vice versa. Tsakiris, Schutz-Bosbach, and Gallagher (2007) stated that ownership does not imply a sense of agency (self-generated movements are not necessary for ownership), but that the sense of agency normally implies ownership. Studies that provide participants with agency toward a fake hand in order to induce a body ownership illusion (Dummer et al., 2009; Sanchez-Vives et al., 2010; Tsakiris et al., 2006; Yuan & Steed, 2010) provide evidence for such a relationship. However, especially in technically mediated scenarios such as in telepresence, this is not necessarily the case. A robot can be controlled from a remote location as an advanced tool, which can thus be embodied based on agency, but where sensory evidence for self-location and body ownership is given toward the physical body. In line with this, in the experiment of Kalckert and Ehrsson (2012), ownership and agency were found to be double dissociated. On the other hand, in the study of Longo et al. (2008) even though participants did not actually move their hands, they nevertheless reported a sense of agency toward the rubber hand. Moreover, Sato and Yasuda (2005), when investigating agency in relation to the predicted (through the efference copy) and actual feedback of actions, proposed that agency is independent of felt body ownership. This is based on the findings that with increased delay between action and feedback, the felt agency was negatively affected, but not the felt self-ownership. Finally, van den Bos and Jeannerod (2002) reported that participants in their study had difficulty judging the ownership of a hand when they did not perform the actions that they saw it do, thus, contradicting the total independence of these two concepts. Finally, concerning the relationship of agency and self-location, the study of David et al. (2006) suggested that the egocentric visuospatial perspective (related to self-location) and sense of agency are independent components of one's self-consciousness.

Despite the lack of sufficient systematic experimental evidence in favor of or against interdependencies between the subcomponents—self-location, agency, and body ownership—the use of virtual reality techniques makes it possible to induce, to a certain extent, the sense of each subcomponent toward a different artificial body. Sensory evidence such as visual perspective can be given from body A such as the participant feels self-located inside A. At the same time, synchronous visuotactile correlations of the same spatiotemporal pattern between the participant's body and another body B of the same appearance, but in a different position, can be used to induce body ownership (although the induced sense might be weak, see Petkova et al., 2011). The physical movements of the participant can also be registered with the seen movements of a third body C inducing the sense of motor control over C. Under such a setup, the sensations associated with embodiment could be theoretically dissociated as coming from three separate bodies; self-location from A, body ownership from B, and agency from C. However, although self-location may be provided with respect to A, it is quite possible that there are effects of this on the other subcomponents; for example, only providing self-location might also lead to a sense of ownership. It is possible using careful experiment design to separate out the unique influences of each subcomponent. This is clearly not easy to do, but it is possible.

In conclusion, little is known about the individual contribution of each component to SoE or whether there is a dominant contribution. The same lack of experimental evidence is apparent when addressing the actual relationship between the three subcomponents; that is, if positive/negative feedback in one of them enhances/inhibits the experience in another. Future studies should aim toward clarifying these open topics systematically.

### 2.6 Measures of the SoE

It is essential to be able to operationalize the concept of SoE for the purposes of measurement. This becomes especially important when the effects of different factors on SoE need to be assessed in an experiment. This is very similar to the concept of presence in virtual environments—a topic that has provoked significant research over many years. Measurement usually relies on questionnaires or physiological responses to anxiety-provoking events in the virtual environment such as Meehan, Insko, Whitton, and Brooks (2002), but where new approaches are also in development (Slater, Spanlang, & Corominas, 2010). However, because of its composite phenomenology, there is not an explicit measure of SoE. Nevertheless, induced SoE toward an artificial body can be approached through measuring it at the level of its subcomponents. An overview of measures used in the literature for addressing SoE is given in Table 2.

**2.6.1 Self-Location.** Recent experimental studies have shown that the normally given coincidence between self and body location can break in experimentally induced out-of-body experiences. These studies used both qualitative (questionnaires) and quantitative (performance in motor or cognitive tasks, physiological responses) measures to investigate illusory self-location and possible deviations from the location of the biological body. In the study of Ehrsson (2007), participants were given a visual perspective from a point in space behind their physical body through a pair of head-mounted displays. Tactile stimulation seen from that position was congruent to felt stimulation on the physical body. Participants experienced the sensation of being located outside their biological body, as reported in questionnaires, and showed higher physiological responses in response to a threat toward this perceived self-location compared to the control condition. Additionally, Lenggenhager et al. (2007) conducted a study where the visual perspective was given from the normal viewpoint. The felt stimulation on the physical body, however, was congruent with the seen stimulation on an artificial body that was in front of the participants. Participants, when passively removed from the scene and asked to return to their initial position, showed a significant drift toward the artificial body. An alternative way to estimate one's perceived self-location through a mental ball-dropping task was proposed by Lenggenhager et al. (2009).

**2.6.2 Agency.** The measurement of agency has not been addressed to the same extent as self-location and ownership. Although there are studies that induce illusory embodiment by providing participants with actual control of the fake limb or body (Dummer et al., 2009; Sanchez-Vives et al., 2010; Tsakiris et al., 2006; Yuan & Steed, 2010), agency in itself toward the embodied object was not the main focus of these experiments. Instead, the control of the fake limb was used in order to generate other illusory sensations in another subcomponent, e.g., ownership. In Kalckert and Ehrs-

**Table 2.** *Overview of Measures of SoE in Terms of its Subcomponents*

| | |
|---|---|
| Sense of self-location | • Questionnaire items; for example, "I experienced that I was located at some distance behind the visual image of myself, almost as if I was looking at someone else" (Ehrsson, 2007, p. 6) [supplemental material].<br>• Estimation of body position: "…passively displacing the blind-folded participants immediately after the stroking and asking them to return to their initial position…" (Lenggenhager et al., 2007, p. 1097) or "…imagine dropping the ball that they were holding in their hand (mental ball dropping task, MBD)." The participants "…were instructed to indicate with a first button press when they imagined releasing the ball from their hand and with a second button press when the ball would hit the ground…" (Lenggenhager et al., 2009, p. 112).<br>• Physiological response in view of a threat toward the perceived self-location; for example, Skin Conductance Response (SCR; Ehrsson, 2007). |
| Sense of agency | • Questionnaire items; for example, "it seemed like I was in control of the rubber hand" (Longo et al., 2008, p. 984), "I felt as if I was controlling the movements of the rubber hand" (Kalckert & Ehrsson, 2012, p. 4). |
| Sense of body ownership | • Questionnaire items; for example, "I felt as if the rubber hand were my hand." (Botvinick & Cohen, 1998, p. 756), "I felt as if the virtual body was my body" (Aspell, Lenggenhager, & Blanke, 2009, p. 4), "How much did you feel that the seated girl's body was your body?" (Slater, Spanlang, Sanchez-Vives, et al., 2010, p. 4), "It seemed like the rubber hand belonged to me" (Longo et al., 2008, p. 983).<br>• Proprioceptive estimations: through intermanual movements; for example, "both before and after the viewing period (…) with eyes closed, the right index finger was drawn along a straight edge below the table until it was judged to be in alignment with the index finger of the left hand" (Botvinick & Cohen, 1998, p. 756; IJsselsteijn et al., 2006), or verbal estimation, "Participants saw a ruler reflected on the mirror. (…) they verbally reported a number on the ruler" (Tsakiris & Haggard, 2005, p. 81).<br>• Estimation of body parts' size; for example, participants "were told to adjust the virtual belly size until they perceived it to be the size of their own real belly" (Normand et al., 2011, p. 3).<br>• Physiological responses to threat; for example, SCR (Armel & Ramachandran, 2003; Honma, Koyama, & Osada, 2009; Petkova & Ehrsson, 2008; Petkova et al., 2011; Yuan & Steed, 2010), Heart Rate Deceleration (Slater, Spanlang, Sanchez-Vives, et al., 2010).<br>• Changes in physiological signals; for example, temperature (Hohwy & Paton, 2010; Moseley et al., 2008). |

son (2012), agency over the rubber hand was addressed qualitatively; for example, by questionnaire. The same measure was used in Longo et al. (2008), a study that was, however, concerned purely with sensation since no actual agency was provided.

**2.6.3 Body Ownership.** SoE at the level of body ownership has been extensively addressed using both qualitative (with questionnaires) and quantitative methods (performance in localization tasks such as proprioceptive drift, performance in body part estimation, participants' reactions under threat of the perceived body, or changes in physiological measurements with or without a threat event). More exploratory studies focused either on exploiting any brain activity changes under body ownership illusions using electrophysiological (Kanayama, Sato, & Ohira, 2009; Peled, Pressman, Geva, & Modai, 2003; Press, Heyes, Haggard, & Eimer, 2008), or hemodynamic (Ehrsson et al., 2004; Ehrsson, Wiech, Weiskopf, Dolan, & Passingham, 2007) methods or on the effect of temporary brain function disruption to the illusion (Kammers et al., 2009; Tsakiris et al., 2008).

The measurements in Table 2 of course do not directly assess the SoE, but act as surrogates. Additionally, one should be aware of conceptual overlaps when using these measures, because the operationalization of the subcomponents is not necessarily mutually exclusive. For instance, the use of proprioceptive drift as a measure of body ownership can be considered to address two underlying subcomponents of embodiment: self-location interpreted as body location, since it is a localization task of a body part; and body ownership, since the task demands the localization of one's own hand. Indeed, in the study of Rohde, Di Luca, and Ernst (2011), proprioceptive drift and ownership were dissociated. Additionally, reactions to a threat are related both to self-location, since such an event contains spatial information (e.g., the proximity of the threat to the perceived self-location) but also to body ownership, because one would manifest strong reactions to a threat in the case where it refers to one's own body, compared to when there is no sensation of ownership. Future studies should correlate both qualitative and quantitative data in order to get a fuller picture of their association with the subcomponents of embodiment (e.g., Ehrsson, 2007; Slater et al., 2008; Slater, Spanlang, Sanchez-Vives, et al., 2010).

Motivated by the lack in the literature of measures for the sense of agency, task performance in motor tasks (including kinematic and physiological analysis) could provide valuable insights into this subcomponent. Based on the assumption that motor tasks are performed more successfully if the artificial body executing the task is under finer control, presumably a high sense of agency should correlate with high task performance. The use of such a measure is in line with the study of Nielsen (1963), where motor performance was used to reveal the mechanisms of body recognition.

Apart from measuring the SoE in the level of its subcomponents, more indirect measures can be outlined from a higher-level perspective concerning its potential psychological, emotional, and behavioral consequences. Such an approach would be in line with the concept of self-presence as firstly depicted by Biocca (1997) who posed the Cyborg's Dilemma. Self-presence (Lee, 2004) considered as "a psychological state in which virtual [. . .] self/selves are experienced as the actual self in either sensory or nonsensory ways" is actually the alteration of the user's behavior or emotional state because of induced SoE toward the given virtual body representation. As proposed by Lee, "intense feelings of self presence during virtual experience (. . .) might create some types of identity or reality confusion." More specifically, if one feels embodied in a virtual body, insults or praise regarding this body, referring to properties that would not be true for the biological body, should cause emotional arousal. For example, in Normand et al. (2011), it was shown that participants could be given the illusion that they were much fatter than their real biological body. It would have been interesting to investigate the correlation between questionnaire items addressing body ownership and those referring to the emotional state; for example, when other virtual characters criticize them for being too fat. Relevant to this is a questionnaire proposed recently by Ratan and Hasler (2009) applied though for less immersive scenarios. Similarly, in Slater, Spanlang, Sanchez-Vives, et al. (2010) male participants experienced the virtual world through the eyes of a girl. However, emotional or behavioral correlates of such virtual representation were not investigated. Generally, a virtual body representation with different morphology with respect to one's own biological properties (e.g., morphological appearance, number of limbs, size), would probably have psychological or even motor consequences. In the studies of Longo, Schuur, Kammers, Tsakiris, and Haggard (2009) and Tsakiris (2008), such consequences were indeed reported. Additionally, a virtual body with characteristics associated with certain social stereotypes but different from those of the biological body (e.g., with respect to race, gender, or age), could result in the participant engaging in behaviors associated with those stereotypes. All these hypotheses could be addressed by future studies in immersive virtual reality systems.

### 2.7 Enhancing the SoE

An approach to enhancing the SoE would be to enhance each of its three subcomponents. We consider each in turn.

**2.7.1 Enhancing the Sense of Self-Location.** Self-location is influenced by the origin of the visual perspective and the associated vestibular and tactile information. Clearly a fundamental requirement is for there to be first-person perspective with respect to the position of the eyes of the artificial body. Additionally, synchronous visuotactile correlations can further strengthen this, where the tactile event is seen visually on the body from the first-person perspective position of the eyes. Lopez et al. (2008) proposed that exposure to caloric and galvanic vestibular stimulation could be used for experimental manipulation of self-location. Therefore, in virtual applications, these various types of manipulation should be considered in order to examine their impact on induced self-location within a virtual body representation. The necessity of such varied multimodal feedback may increase in importance the more the virtual body volume varies from that of the real biological body.

**2.7.2 Enhancing the Sense of Agency.** The sense of agency is sensitive to any temporal discrepancies between the execution of a self-generated movement and visual feedback. Hence, visuomotor correlations should be provided maintaining critical time boundaries (see Franck et al., 2001). The sense of agency is easily provided in virtual reality when the motion of the participant is mapped to the virtual body in real-time or near real-time. This can be achieved either by tracking rigid bodies (by rigid reflective markers) attached to the participant's limb and computing the avatar's movement by an inverse kinematics method (Yuan & Steed, 2010), or by tracking the full-body movements of the participant with a real-time motion capture system and applying the resulting motion to the avatar (Slater, Spanlang, & Corominas, 2010).

**2.7.3 Enhancing the Sense of Body Ownership.** The sense of body ownership, from the perspective of bottom-up influences, can be enhanced by increasing the sensory correlations between the physical stimulation of the biological body and the seen stimulation on the avatar's body. Such synchronous sensory correlations can be either visuotactile (e.g., with the use of appropriate haptic feedback), or visuoproprioceptive (e.g., by the participant's passive movements and appropriate avatar animation). On the other hand, the virtual body should obey certain structural and morphological constraints in order to appear human-like. By maximizing the morphological similarity between one's biological body and the virtual one, top-down influences favor the perception of ownership of the virtual body. In contrast to the previously mentioned categories, the sense of body ownership may be highly susceptible to individual differences; for example, the similarity in appearance between the participant and the avatar. In line with this, individualized avatars could strengthen ownership since this would also promote body and self-recognition.

## 3 Conclusions

The present review has discussed a working definition for SoE by relating it to the normal embodiment we experience toward our biological body. An underlying structure was proposed, consisting of three subcomponents: sense of self-location, sense of agency, and sense of body ownership. Measures of the SoE as used in the literature were grouped and organized under this conceptualization. Moreover, new possible measures based on the psychological and emotional consequences of embodiment and methods for the enhancement of the SoE in virtual reality through its subcomponents were suggested.

Throughout the paper, several challenges became apparent. Possible directions for future studies that aim toward a deeper and more precise conceptualization of SoE were outlined. Whereas SoE may consist of three subcomponents, their relationship is far from understood. Although these may be conceptually independent, it is quite probable that there is an empirical correlation between them. Future studies are needed to detect the existence, if any, of such dependencies. Additionally, there is no evidence for an equal contribution of each subcomponent to the overall concept of embodiment. If embodiment is a weighted combination of these, future studies with experimental conditions that manipulate different subcomponents could shed light on the potential dominance of a subcomponent.

The present paper focused on artificially induced embodiment and more especially on using immersive virtual reality for this purpose, a technology that seems ideally suited to tackle research in this area. Based on the current overview and proposed future studies, new insights into this complex experience might be found and precise guidelines could be provided toward the enhancement of the sense of embodiment.

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