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Review article

The role of *functionality* in the body model for self-attribution

Laura Aymerich-Franch, Gowrishankar Ganesh*

CNRS-AIST JRL (Joint Robotics Laboratory), Japan

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ABSTRACT

Bodily self-attribution, the feeling that a body (or parts of it) is owned by *me*, is a fundamental component of one's self. Previous studies have suggested that, in addition to a necessary multi-sensory stimulation, the sense of body ownership is determined by the body model, a representation of our body in the brain. It is however unclear what features constitute the body representation. To examine this issue, we first briefly review results on embodiment of artificial limbs, whole bodies and virtual avatars to understand the apparent anatomical, volumetric and spatial constraints associated with the sense of ownership toward external entities. We then discuss how considering limb *functionality* in the body model can provide an integrated explanation for most of the varied embodiment results in literature. We propose that the self-attribution of an entity may be determined, not just by its physical features, but by whether the entity can *afford* actions that the brain has associated with the limb which it replaces.

Contents

1. Introduction

Who am I? The question of what is our self and how our brain defines self has been a fundamental motivation that has driven philosophy (Kant, 1781; Descartes and Cottingham, 2013), psychology (James, 1890; Jung, 1971) and religion (Rāhula, 1959; Sivananda, 1972) over the course of the human existence. The Oxford dictionary (Oxford English Dictionary, 2010) defines self as "a person's essential being that distinguishes them from others, especially considered as the object of introspection or reflexive action." However, it will be generally agreed that this simple definition is far more complex than perceived. Self can be defined in multiple terms from one's physiology, mental and emotional status to beliefs, social status and spiritual being (closely related to the concept of soul). It can include various facets like *self-image, self-perception, ideal-self* and *self esteem*. For instance William James, the well-known 19th century philosopher, divided self into two main categories. The "Me" self, and the "I" self (James, 1890). The "Me" self, which he further

* Corresponding author at: CNRS-AIST JRL (Joint Robotics Laboratory), UMI3218/CRT, Tsukuba Central 1, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8560, Japan. Tel.: +81 9081241047.
E-mail address: gans_gs@hotmail.com (G. Ganesh).

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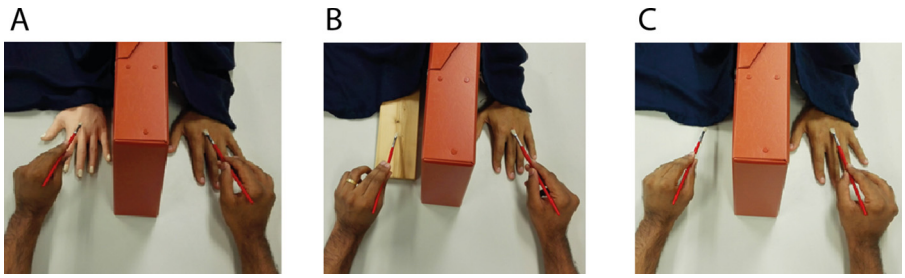

Fig. 1. The rubber hand illusion (RHI) has been a standard to investigate the sense of ownership over the past decade. (A) The original RHI involves simultaneous brushing of the real hand and a rubber hand in view of the subject. (B) The illusion is not induced if the rubber hand is replaced by a "non-corporeal object" (Guterstam et al., 2013; Tsakiris and Haggard, 2005) but is reportedly possible when (C), the brushing is done on an empty volume of safe. Figures from experiments reconstructed by the authors from (Guterstam et al., 2013).

divided into the material self, the social self, and the spiritual self, refers to the aspects of someone that come from that person's experiences. On the other hand, James saw the "I" self as the thinking self and linked this self to the soul or mind of a person.

In this short review, we will limit ourselves to discussing bodily *self-attribution* and specifically to what constitutes the *body model* utilized by the brain for self-attribution. The self we will explore is probably best defined as the bodily *self image* and by James Williams's definition, part of the "material self".

Bodily self-attribution or *body-ownership* is a crucial component of the self. Body ownership refers to the *special* perceptual status of one's own body, which makes bodily sensations seem unique to oneself (Gallagher, 2000; Tsakiris, 2010), that is, the feeling that certain limbs and certain sensed body belongs to me. It is well established that illusory changes in the feeling of body ownership can be generated by correlated stimulations in different combinations of sensory modalities (Botvinick and Cohen, 1998; Armel and Ramachandran, 2003; Ehrsson et al., 2005; Tsakiris et al., 2006; Walsh et al., 2011; Kalckert and Ehrsson, 2012). However, while multi-sensory stimulations are necessary, they are arguably not sufficient to induce the feeling of ownership. Multiple studies have shown that the feeling of ownership toward an artificial limb is additionally modulated by its anatomical (Tsakiris and Haggard, 2005; Haans et al., 2008; Guterstam et al., 2013), volumetric (Pavani and Zampini, 2007), and spatial (Pavani et al., 2000; Austen et al., 2004; Ehrsson et al., 2004; Tsakiris and Haggard, 2005; Costantini and Haggard, 2007; Lloyd, 2007) features. These results support the belief that, in addition to the *bottom-up* multi-sensory perception, self-attribution is regulated by a *top-down* perceptual *body model*, a reference description of our body or/and the space around it in our brain (De Vignemont et al., 2006; Makin et al., 2008; Tsakiris, 2010; Blanke, 2012; Moseley et al., 2012). The specific bodily features that the body model encodes, however, remain unclear.

In this article we will examine what minimal features can explain how our brain represents our body. First, we will briefly review studies on *embodiment* of artificial limbs, whole bodies and virtual avatars to explore the apparent "top-down" constraints associated with the illusion of body ownership. While the definition of embodiment is varied, at least in the case of artificial limbs and bodies, embodiment is generally agreed to include the sense of ownership. We will thus assume embodiment to represent ownership in this article. Following the review, we will propose limb *functionality* as the key feature of the body model, and discuss how a body model considering functionality can explain most observations by previous studies.

2. The rubber hand and beyond

Our understanding of body ownership has increased significantly in the last decade after the discovery of the *rubber hand illusion* (RHI) (Botvinick and Cohen, 1998) which enables controlled manipulation of limb ownership in the laboratory environment. As is customary with articles dealing with body-ownership, we too will start with a brief description of the RHI. In this illusion, Botvinick and Cohen showed that synchronous touches, applied to a rubber hand in full view of the participant, and the real hand hidden behind a screen, produce the sensation that the touches felt originate from the rubber hand, leading to a feeling of ownership of the artificial rubber hand. In contrast, the illusion of ownership is absent if the touches on the rubber hand and the real hand are not synchronized.

Since the first experiment, multiple versions of the RHI have examined how different physical and spatial features of the rubber hand influence the illusion (Fig. 1). While the similarity of physical features of an embodied artificial limb and the real limb does aid self-attribution, subjects are able to embody limbs with different physical features. It has been shown that color does not determine embodiment of an artificial limb (Holmes et al., 2006; Longo et al., 2009). For instance, Holmes et al. (2006) found that a white rubber hand produced similar levels of embodiment in white and black skin participants. Longo et al. (2009) found that objective similarity (as measured by skin luminance, hand shape, and third-person similarity ratings) did not affect fake limb embodiment. Similarly, a rubber hand with a different skin texture can be embodied, even though the embodiment scores are reportedly lower (Haans et al., 2008). In regard to size, it has been shown that a rubber hand larger than one's real hand (Pavani and Zampini, 2007) and longer arms (Schaefer et al., 2007; Kilteni et al., 2012) can be embodied by subjects, while interestingly, a rubber hand smaller in size than one's real hand is not (Pavani and Zampini, 2007). Smaller size though is no problem when it comes to whole body embodiment as shown by an attractive study by Ehrsson and colleagues (Van der Hoort et al., 2011) where they embodied subjects into dolls ranging in size from 30 cm to 400 cm.

Similar results have been reported for whole body embodiment in virtual reality (VR). Studies that use this technology typically induce embodiment by giving users visual feedback in first person perspective of the virtual environment, which is displayed in accordance to their head movements. VR users are generally able to see the virtual limbs of their avatars in a coincident location with that of their real limbs. Additionally, full-body identification with the digital self-representation (i.e. the avatar) can be achieved by reflecting the avatar's body in mirrors or other reflecting surfaces (González-Franco et al., 2010; Aymerich-Franch et al., 2014), so users gain knowledge of how they look like in the virtual environment. Resemblance of the artificial body to a human body improves embodiment into the avatar (Maselli and Slater, 2013), and the feeling of *Presence* (discussed also in the next section) in the virtual world (Eastin, 2006; Ratan et al., 2007; Ratan, 2011). Furthermore, customization of avatars increases the extent to which people feel connected to