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The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership

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ABSTRACT

The rubber hand illusion is a perceptual illusion in which a model hand is experienced as part of one's own body. In the present study we directly compared the classical illusion, based on visuotactile stimulation, with a rubber hand illusion based on active and passive movements. We examined the question of which combinations of sensory and motor cues are the most potent in inducing the illusion by subjective ratings and an objective measure (proprioceptive drift). In particular, we were interested in whether the combination of afferent and efferent signals in active movements results in the same illusion as in the purely passive modes. Our results show that the illusion is equally strong in all three cases. This demonstrates that different combinations of sensory input can lead to a very similar phenomenological experience and indicates that the illusion can be induced by any combination of multisensory information.

1. Introduction

The rubber hand illusion is a perceptual illusion in which participants experience a fake model hand as being part of their own body. In the classical version, a rubber hand is placed in front of the participant and synchronous touches are applied to the rubber hand and the participant's real hand, which is hidden from view (Botvinick & Cohen, 1998; Ehrsson, Spence, & Passingham, 2004; Tsakiris & Haggard, 2005). After a short period, within less than a minute and often as quickly as 10 s (Ehrsson et al., 2004; Lloyd, 2007), participants start to feel as if the touch they sense originates from the location on the rubber hand where they see the brush touching the rubber hand, rather than from their real hand. They also start to experience the feeling that the rubber hand is their own hand (*sense of body ownership*), a feeling that can be quite vivid in many participants. The illusion is often explained as a result of the elimination of the initial conflict between visual and somatosensory representations of the hand and the integration of visual, tactile and proprioceptive signals, that leads to a coherent multisensory perception of the model hand as one's own hand receiving the touches (Ehrsson, 2012; Makin, Holmes, & Ehrsson, 2008). Because the illusion involves consciously felt changes in ownership of the model hand, it has become a very popular model system to study issues related to bodily self-consciousness (Blanke, 2012), subjective embodiment (Tsakiris, 2009), and how the brain makes the perceptual distinction between the physical self and the external environment (Ehrsson, 2012; Petkova et al., 2011).

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Recent behavioral experiments have demonstrated that the rubber hand illusion can be elicited by finger movements alone rather than by combined tactile and visual stimulation with an external probe, as in the classical version (Dummer, Picot-Annand, Neal, & Moore, 2009; Kalckert & Ehrsson, 2012; Tsakiris, Prabhu, & Haggard, 2006; Walsh, Moseley, Taylor, & Gandevia, 2011). In our version of the moving rubber hand illusion (Kalckert & Ehrsson, 2012), every time the participant moves his index finger, which is hidden from view under a box, the index finger of a wooden model hand moves synchronously in the same way. This elicits a strong sense of ownership of the model hand and finger, regardless of whether the finger movements are actively produced by the participants or passively by the experimenter. In the case of active movements, the participants also experience a vivid sense of being in voluntary control of the model hand's actions; that is, they experience a *sense of agency* of the model hand (David, Newen, & Vogeley, 2008). This happens because, unlike in passive conditions, the participants form motor intentions to move the model hand. Once the predicted sensory consequences of the movements also match the actual sensory feedback, one experiences the movement as self-produced as opposed to being produced by an external force (Crapse & Sommer, 2008; Holst & Mittelstaedt, 1950). The information related to the sense of agency can serve as an another source of information for the process of self-recognition, complementing the sense of ownership (Gallagher, 2000; Kalckert & Ehrsson, 2012).

The moving rubber hand illusion raises several important questions. First, one can ask whether movements lead to a stronger illusion because more channels of sensory information are available than in the classical rubber hand illusion (Botvinick & Cohen, 1998). During movement, not only are cutaneous afferents signaling skin stretching engaged (Edin & Johansson, 1995) but also muscle spindle receptors and joint receptors are engaged (Proske & Gandevia, 2012). None of these are stimulated by the tactile stimulation used in the classical rubber hand illusion. Second, one can ask whether efferent signals from the motor commands contribute to the feeling of ownership when the finger is moved voluntarily. We know that visual perception is influenced by efferent copy signals from oculomotor areas, and the possible role of efferent signals in kinesthesia has been discussed for over a century (Gandevia, Smith, Crawford, Proske, & Taylor, 2006; Matthews, 1982); thus, similar effects on body ownership by efferent signals might be expected. However, these questions have not been resolved in previous literature. The earlier studies investigating moving rubber hand paradigms have used different setups and found apparently conflicting results when comparing active movements, passive movements and visuotactile stimulation. Tsakiris and colleagues (2006), using a video-screen-based setup, found no difference in the strength of the proprioceptive drift between conditions in which the illusion was elicited by active movements, passive movements or visuotactile stimulation. Dummer and colleagues (2009), using whole hand movements, measured the subjective strength of the illusion and found stronger ratings of ownership during active movements than during passive movements, but ratings during visuotactile stimulation were again higher than during active movements (in a between-group design). Finally, Longo and Haggard (2009), using a setup in which a video image of the hand was presented on a screen, analyzed questionnaire data that revealed a main effect of induction type across active, passive, and visuotactile stroking conditions, without specifying the exact relationship among the different types. Kammers and colleagues (2009) also used a video screen based setup to compare proprioceptive drift after active and passive movements and found that the drift was pronounced when testing using a manual pointing response, but not when using a perceptual judgment procedure. More recently, Riemer and colleagues (2013) compared active movements and visuotactile stimulation and found equally strong subjective ratings. However, when testing proprioceptive drift with a perceptual judgment or manual pointing procedure they found that a significant proprioceptive drift associated with the moving rubber hand illusion could only be detected when using the manual pointing procedure. Finally, experiments with fully simulated moving hands in virtual reality have also been performed (Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008) but these do not directly resolve the issues discussed in the literature.

In our previous study (Kalckert & Ehrsson, 2012), we systematically manipulated the spatial orientation of the model hand (aligned with the participant's hand or rotated 180°) and the timing of the visual feedback and somatosensory feedback (synchronous or asynchronous). This allowed us to show that the moving rubber hand illusion depends on the same temporal congruency and anatomic plausibility rules as the classical rubber hand illusion (Ehrsson et al., 2004; Tsakiris & Haggard, 2005), that is, that asynchronous feedback or rotating the model hand 180° breaks the illusion of ownership (Kalckert & Ehrsson, 2012). Moreover, with this design, we were able to dissociate sense of ownership and agency and show that agency could be experienced for the rotated model hand placed in the anatomically implausible position during which participants explicitly rejected feeling ownership. Interestingly, we also noted a small but significant increase in ownership ratings when we directly compared active synchronous movements to passive synchronous movements, although no difference was observed in proprioceptive drift measurements. Thus, given the heterogeneity in the methodology and results of earlier studies, our own included, it is not clear what effect the type of induction has on the rubber hand illusion.

In the present study, we re-examined these questions in experiments where we directly compared the rubber hand illusion as elicited by active movements, passive movements, or visuotactile stimulation. In the first experiment, we measured the subjective experience of ownership of the model hand in the three versions of the rubber hand illusion outlined above and quantified the sense of agency in all experimental conditions. In the second experiment, we compared the strength of the illusion induced by active movements or visuotactile stimulation by measuring changes in the felt position of the participant's real hand using a proprioceptive drift measurement. Our results show that all three modes of inducing the illusion – active movements, passive movements, and visuotactile stimulation – elicited a similarly strong rubber hand illusion. Moreover, across individuals, the strength of the ownership illusion was correlated across the three illusion types. These