

Movement and the rubber hand illusion

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Abstract. When a participant views a rubber hand being stroked by a paintbrush while his/her real hand is unseen and similarly stroked by another paintbrush, a misperception known as the rubber hand illusion occurs whereby tactile sensations are falsely referred to the non-body part. The purpose of the current study was to further examine the rubber hand illusion with conditions of movement. An apparatus was devised that would synchronise visual with felt movement in an active condition and a passive condition. An asynchronous condition was included as a control in which visual and felt movement were purposely disconnected. The three movement conditions (active, passive, and asynchronous) were statistically compared in order to assess our prediction that synchronous conditions of movement (especially active) would generate more reports of the illusion. The performance of the movement conditions was evaluated against a visual-tactile condition, which is a known contributor to the rubber hand illusion. Not only significantly more robust reports of the illusion were obtained when visual movement and felt movement were synchronised but there was also a trend toward stronger reports in the active condition rather than the passive condition. Interestingly, the pattern of results differed according to the particular question on the self-report.

1 Introduction

How is it that we automatically perceive our hand as a functional component of the bodily self? Some insight into this question can be gained by examining situations in which misperception of false body parts occurs in cognitively unimpaired people. Botvinick and Cohen (1998) first reported a curious illusion in which participants viewed a rubber hand being stroked by a small paintbrush in precise synchrony with their own visually occluded hand, and as a result falsely referred the tactile sensations to the rubber hand. In effect, participants perceived the tactile stimulation of their own hand from a different proprioceptive location—that of the rubber hand. In a post-experiment questionnaire, participants were asked to confirm or deny whether each of nine distinct perceptual effects had occurred as a result of the manipulation. Interestingly, the resultant pattern of scores suggested that participants had mistakenly regarded the rubber hand as a genuine component of their body. This finding, known as the rubber hand illusion (RHI), led Botvinick and Cohen (1998) to reason that identification of the bodily self is achieved through the spatiotemporal integration of multisensory information—in this case visual information matched with tactile information.

In the RHI, the dual sources of sensory stimulation occur together but are spatially incompatible, similar to the case of ventriloquism where the source of vocal sounds appears to originate from the moving mouth of a dummy. In an attempt to coordinate and resolve the perceptual incongruity, the real hand is mentally remapped closer to the location of the rubber hand. This distortion of body sense occurs because, in this case, vision overrides the tactile sense such that with enough experience and repetition what is viewed becomes the source of felt stimulation (Botvinick 2004; Eimer 2004; Ernst and Banks 2002; Graziano 1999). Importantly, conditions of multisensory integration (eg visual paired with tactile sensation) can also lead to a misperception of the rubber hand. Initially, this misperception was believed to involve the incorporation or

adoption of the rubber hand into the bodily self as an auxiliary (although false) body part (Botvinick 2004; Botvinick and Cohen 1998). However, according to Longo et al (2008), this misperception more likely involves a temporary displacement or deletion of the real hand in favour of the rubber hand. Thus, instead of becoming a perceptual adjunct to the body schema, the rubber hand in effect replaces the real hand. This could occur because plasticity in this case is limited by the principles of body constancy and body image stability (Feiner 1987); therefore, the rubber hand can only be incorporated into the body schema by mentally suppressing the existing hand (Longo et al 2008).

Body perception is not limited to tactile information. Proprioception provides additional information that may also lead to an RHI under appropriate conditions. Previous research has shown that recognition of one's hand becomes significantly more accurate when one is the author or source of an action (Tsakiris et al 2005). In the above study, extension of the subject's right finger occurred as a result of either self-generated action (subject's left hand operated a lever that controlled extension of the right finger) or externally generated action (experimenter operated the lever). Subjects viewed either their own hand or the experimenter's hand on a video display and responded "yes" if they believed the hand on the display was their own hand. Importantly, afferent (ie visual and proprioceptive sensation) information was comparable across conditions such that the only difference was the degree of efferent (ie motor command) information. Results showed that participants' recognition of their hand was significantly more accurate when movement was self-generated. Tsakiris et al (2005) attributed this finding to an authorship effect on self-recognition, which has been corroborated by similar perceptual research (Tsakiris and Haggard 2003). Given the above finding and the hypothesised importance of visual-proprioceptive integration (Bahrack and Watson 1985; Hiraki 2006; Miyazaki and Hiraki 2006; Rochat 1998) in the origins of self-identification and self-other discrimination, we reasoned that proprioceptive experience would prove to be a strong contributor to the RHI. This reasoning is rooted in a landmark study conducted by Bahrack and Watson (1985) in which two monitors were presented to infant subjects—one displaying recorded video footage of the subject's leg movements and the other recorded video footage of another infant's leg movements. Using visual preference procedures, the researchers found that infants of 4–5 months of age could discriminate their leg movements from recorded video of the other infant's leg movements (Bahrack and Watson 1985). Hence, active movement and proprioceptive sense could perhaps be used to generate the RHI.

The purpose of the current study was to determine: first, whether conditions of synchronous visual-proprioceptive experience would elicit the RHI; and, second, whether active movement would facilitate more robust reports of the illusion than passive movement. Active and passive movements both activate proprioceptive sensory pathways regarding changes in body position. However, active movement is unique in that it is initiated and controlled by the individual. As such, active (ie voluntary) movements have a distinctive temporal structure: (i) initial generation of the intention to move; (ii) mobilisation of the prevailing motor command associated with the particular movement (ie efference copy); (iii) execution of the movement; (iv) perception of the effects of the movement (Gallagher 2000; Tsakiris and Haggard 2005a, 2005b). Because of this, active movement is believed to provide not only self-specifying proprioceptive feedback regarding the particular movement but also subjective feelings of controlling one's own body movements (see Tsakiris and Haggard 2005a; Tsakiris et al 2006).

For the current study, synchronisation of visual with proprioceptive sensory input was accomplished with a brace that connected the participant's real hand with a rubber hand, both of which were suspended in mid-air to facilitate unimpeded motion. By means of this design, movement of the participant's hand would be tightly correlated

in spatiotemporal properties relative to the concomitant movement of the rubber hand. In other words, movement of the real hand and the rubber hand would occur at the same time and proceed in the same manner (eg same direction, same speed, and same trajectory). The main factor was the particular condition of movement with three independent conditions implemented. First, in order to provide a baseline against which the visual-proprioceptive movement conditions could be compared, an asynchronous visual-proprioceptive condition was arranged. In this condition, viewed movement of the rubber hand was deliberately disconnected from felt movement of the real hand. This control condition was analogous to the asynchronous visual-tactile condition in Botvinick and Cohen's (1998) study in which the tactile stimulation of the real hand and the rubber hand occurred asynchronously. Second, a synchronous visual-proprioceptive active movement condition was designed in which movement was initiated and performed by the participant. In order to assess the role of efference (over and above proprioception) in body perception, we included a passive condition in which hand movements of each participant were initiated and controlled by the experimenter.

An additional comparison condition was incorporated in order to assess the strength and/or authenticity of the RHI reports generated by the movement conditions. Previous research has reported the efficacy of synchronous visual-tactile sensation in eliciting the RHI (Botvinick and Cohen 1998; Tsakiris and Haggard 2005b) and improving tactile sensitivity in clinical patients (Rorden et al 1999). Tsakiris and Haggard (2005b) assessed the role of body scheme representations on the RHI using a visual-tactile procedure. The authors found that the RHI could be successfully elicited by the synchronisation of visual and tactile information but only when the rubber hand closely matched the participant's hand in terms of posture, relative position, and appearance. Because of the above findings, we included a visual-tactile condition in the current study to provide a comparison known to produce robust RHI reports.

We predicted significantly more instances of the RHI in the synchronous visual-proprioceptive conditions than in the asynchronous visual-proprioceptive condition. This hypothesis stemmed from Botvinick and Cohen's (1998) report that identification of the bodily self is achieved through the integration of multisensory information. We also predicted that the active movement condition would generate significantly more RHI reports because of the added influence of the motor command. We did not have clear predictions about how RHI scores elicited from the visual-proprioceptive conditions would compare with those elicited from the visual-tactile condition.

2 Method

2.1 Participants

Participants were recruited through an undergraduate Introductory Psychology subject pool and were provided an incentive of one course credit point for participation. In total, fifty-two participants were included in the current study, with fourteen participants in each of the three movement conditions and ten participants in the visual-tactile condition. All participants had normal vision or corrected vision by means of prescribed corrective lenses.

Approximately two thirds of the participants across movement conditions were female (67%). The average age of participants was 19 years ($SD = 1.6$ years) with a range of 17 to 24 years. Fifty-one participants were right-handed (98%).

2.2 Apparatus

A purpose-built wooden table with a standing black canvas screen halfway along its length was constructed. A solid wooden frame was mounted on the table to allow for the suspension of the real and rubber hands during the movement conditions. For all conditions, a brace was used that was constructed from a wooden dowel rod with an

adjustable cuff at either end. On one end of the brace, a dowel rod extended beyond the outer cuff to allow for externally directed movement during the passive and asynchronous conditions.

For the synchronous visual-proprioceptive conditions, the dowel rod passed through a slit in the central screen so that participants could watch the rubber hand while their real hand moved unseen on the other side of the screen (see figure 1). For the asynchronous visual-proprioceptive condition an additional screen was positioned on the left side of the participant and equidistant from the experimenter's seating location. This screen concealed the participants' view of the experimenter manipulating the movement of the rubber hand from the left side of the participants.



Figure 1. [In colour online, see <http://dx.doi.org/10.1068/p5921>] Photograph of the apparatus used for the synchronous visual-proprioceptive movement conditions.

An artificial human hand made of rubber was purchased from an online novelty shop specialising in realistic artificial limbs. The rubber hand displayed the usual surface features associated with a human hand such as bumps, lines, and creases. Wristbands were used for comfort and to cover the participants' right wrists and the wrist of the rubber hand.

2.3 Measures

The RHI was measured with a self-report pen and paper questionnaire adapted from Botvinick and Cohen (1998) and comprised five questions on a 7-point Likert scale. The five questions were chosen on the basis of those that could be reasonably adapted to the current study. Numbers on the scale represented 'levels' of agreement with the provided statement. The RHI self-report was tailored to each condition by rewording the first two questions (see table 1).

2.4 Procedure

For both synchronous visual-proprioceptive conditions, the wooden rod was inserted through a slit in the central screen and the rubber hand was cuffed into the brace. In addition, a canvas sling was suspended from the overhanging wooden frame to support the participant's right arm during the movement conditions. The right-oriented rubber hand was suspended by fishing line at an approximately equivalent height as the participant's right hand. Participants in the active movement condition were instructed

Table 1. Self-report response sheets for the visual-tactile condition and synchronous and asynchronous visual-proprioceptive conditions. Note that the first two questions differ according to the particular condition: visual-tactile (V-T) versus synchronous and asynchronous visual-proprioceptive (V-P). The remaining three questions were identical across individual self-reports.

Please circle the number that indicates the truth of the statement, with 1 indicating strongly disagree and 7 strongly agree.		1	2	3	4	5	6	7
1.								
V-T:	It seems as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand touched.							
V-P:	I felt I was moving in relation to where I saw the rubber hand moving rather to where I knew my own hand to be moving.							
2.								
V-T:	It seemed as though the touch I felt was caused by the paintbrush touching the rubber hand.							
V-P:	It felt as if the movement I felt was caused by the movement of the rubber hand.							
3.	I felt as if the rubber hand were my own hand.							
4.	It seemed as if I might have more than one right/left hand or arm.							
5.	It felt as if my (real) hand were turning rubbery.							

to move their arm continuously in a horizontal plane while being exposed to the similarly moving rubber hand. Participants in the passive movement condition were instructed to relax their right arm and to not resist the ensuing movement. By manipulating the extended rod, the experimenter was able to coordinate controlled and continuous movements throughout the brace for each participant in the passive condition. For both the active and passive conditions, movements of the brace produced corresponding (and equivalent) changes in the spatial location of the real and rubber hands.

Similar to the above movement conditions, participants in the asynchronous visual-proprioceptive condition were asked to wear the wristband on their right wrist and place their right arm comfortably in the sling. In this condition, however, participants were not cuffed and as such were disconnected from the brace and movement of the rubber hand. Participants were instructed to engage in a continuous random movement with their right arm during which time the experimenter conducted the movement of the rubber hand. The operation of the asynchronous condition was essentially the reverse of the passive movement condition, with the exception that the participant remained uncuffed. In this way, the rubber hand (controlled by the experimenter manipulating the brace) moved independently of the participant's right hand.

The visual-tactile condition represented a replication of the original Botvinick and Cohen paradigm. The experimenter sat facing the participant on the opposite side of the table and used a thin paintbrush to gently and repeatedly stroke both the participant's real right hand and the rubber hand simultaneously for a period of 10 min. The brush strokes occurred randomly starting in the middle of the back of the hand and ending on the knuckles or between the fingers.

For all four conditions, participants were instructed to watch the rubber hand for 10 min. Participants were also instructed to keep their right hand flat with the palm pointing down either above the surface of the table (for the movement conditions) or resting directly on the table (for the visual-tactile condition). Participants were reminded to focus on the rubber hand in front of them for the entire duration of 10 min while their right hand remained hidden on the other side of the table.

3 Results

Two main hypotheses regarding the role of movement in the generation of the RHI were tested statistically. (i) Significantly higher RHI scores would be observed in the visual-proprioceptive synchronous conditions than in the visual-proprioceptive asynchronous condition; and (ii) significantly higher RHI scores would be observed in the active condition than in the passive condition. Because we expected robust RHI reports from the visual-tactile condition, it served as an appropriate comparison condition against which the performance of the movement conditions could be statistically evaluated. The dependent variables were primarily the total score on the RHI self-report questionnaire and secondarily the score on each questionnaire item. The aggregate score of questions 1 to 3 (Q1–Q3) was also included as a dependent variable in the analysis, because Q1–Q3 had yielded particularly high scores in Botvinick and Cohen (1998). Descriptive statistics were calculated for each condition and for each measure (see table 2). A preliminary analysis failed to evidence any sex-related or age-related differences in RHI scores.

Table 2. Mean scores for each of the dependent measures with standard deviations in parentheses. Note that the dependent measures ‘total’ and Q1–Q3 (questions 1–3) were obtained by summing the scores for all five questionnaire items and first three individual questionnaire items, respectively. Averag(ing) represents the average score on the self-report questionnaire for ‘total’ and Q1–Q3.

Condition	Dependent measure								
	Q1	Q2	Q3	Q4	Q5	total	average total	Q1–Q3	average Q1–Q3
Active	4.9 (1.2)	4.5 (1.7)	4.2 (1.4)	3.9 (1.9)	4.1 (1.7)	21.7 (4.9)	4.3 (1.0)	13.6 (3.8)	4.5 (1.3)
Passive	3.3 (1.5)	3.8 (1.7)	3.8 (1.7)	3.1 (1.8)	3.5 (2.3)	17.4 (6.7)	3.5 (1.3)	10.9 (4.3)	3.6 (1.4)
Asynchronous	3.0 (1.5)	3.1 (1.5)	1.8 (1.1)	1.9 (1.5)	2.8 (1.7)	12.6 (5.3)	2.5 (1.1)	7.9 (3.5)	2.6 (1.2)
Tactile	5.9 (1.3)	4.4 (1.5)	5.1 (1.1)	2.6 (1.6)	3.6 (1.7)	21.6 (4.0)	4.3 (0.8)	15.4 (2.5)	5.1 (0.8)

To examine the overall role of movement in the RHI, a between-subjects one-way ANOVA with movement condition as the independent factor was conducted with total score as the dependent variable. This analysis on total score yielded a significant effect of movement condition ($F_{2,39} = 9.1, p < 0.05, \eta_p^2 = 0.32$). An analysis of Q1–Q3 also yielded a significant effect of movement condition ($F_{2,39} = 7.8, p < 0.05, \eta_p^2 = 0.28$). To evaluate the first hypothesis regarding the role of synchronous visual-proprioceptive movement, an independent group *t*-test comparing both synchronous visual-proprioceptive conditions together with the synchronous visual-proprioceptive condition was conducted with total score as the dependent variable. This analysis showed that the synchronous conditions led to a higher RHI score than the asynchronous condition ($t_{40} = 3.6, p < 0.05$). A similar analysis on Q1–Q3 also showed that the synchronous conditions led to a higher RHI score than the asynchronous condition ($t_{40} = 3.3, p < 0.05$). To evaluate the second hypothesis regarding the role of active movement, an independent group *t*-test comparing the active movement condition with the passive movement condition was conducted with total score as the dependent variable. This analysis showed a nearly significant difference between the two synchronous conditions with a higher RHI score in the active condition ($t_{26} = 1.9, p = 0.06$). As before, an analysis of Q1–Q3 revealed a similar trend ($t_{26} = 1.8, p = 0.08$). Because of the statistical similarity between the total score (representing all five questions) and the total

of the first three questions, the remaining analyses included the total score as the main dependent variable.

Examination of the descriptive statistics in table 2 shows that the size of the movement condition effects appeared to vary for different questions in the self-report measure. Therefore, *a posteriori* between-subjects one-way ANOVAs with movement condition as the independent factor were performed on the mean score for each question. α was set at a value of 0.01 for the *a posteriori* tests. These analyses yielded significant effects of movement condition for Q1 ($F_{2,39} = 7.4$, $p < 0.01$, $\eta_p^2 = 0.28$) and Q3 ($F_{2,39} = 11.3$, $p < 0.01$, $\eta_p^2 = 0.37$), along with a near-significant effect for Q4 ($F_{2,39} = 4.7$, $p = 0.015$, $\eta_p^2 = 0.19$). A comparison of the active and passive movement conditions on mean scores revealed a significant mean difference for Q1 ($p < 0.01$). A comparison of the active and asynchronous conditions on mean scores revealed significant mean differences for Q1 ($p < 0.01$) and Q3 ($p < 0.01$), along with a near-significant mean difference for Q4 ($p = 0.012$). A comparison of the passive and asynchronous conditions on mean scores showed a significant mean difference for Q3 only ($p < 0.01$).

To evaluate the performance of each movement condition relative to the visual-tactile condition, three separate independent samples *t*-tests were performed with total score as the dependent variable. These analyses yielded: (i) a significant difference between the asynchronous movement and visual-tactile conditions ($t_{22} = 4.6$, $p < 0.05$); (ii) no significant difference between the passive movement and visual-tactile conditions ($t_{22} = 1.8$, $p = 0.09$); and (iii) no significant difference between the active movement and visual-tactile conditions ($t_{22} = -0.06$, $p = 0.95$).

4 Discussion

In this study we sought to advance current research on the RHI by using a novel visual-proprioceptive manipulation that directly tied the seen movements of a rubber hand with the proprioceptive signals generated by the movements of a real hand. Three movement conditions were compared. Two conditions involved synchronous visual and proprioceptive information and these conditions yielded higher RHI reports than a condition in which visual and proprioceptive informations were asynchronous. RHI reports from these synchronous movement conditions did not differ significantly from those of a comparison visual-tactile condition. These findings indicate that synchronous visual and proprioceptive information, like synchronous visual and tactile information, can lead to a misperception of the rubber hand. It appears then that the RHI may be a phenomenon contingent on the detection of self-specifying intersensory correlations (Ehrsson et al 2005; Rorden et al 1999) and influenced by top-down conceptual representations (Costantini and Haggard 2008; Lenggenhager et al 2007; Tsakiris and Haggard 2005b).

Previous research has also identified active movement as an important component of the RHI and body perception (eg Roessler and Eilan 2003; Tsakiris and Haggard 2003; Tsakiris et al 2005, 2006; Van den Bos and Jeannerod 2002), because the relationship between actions and sensory components (ie planned and initiated movement followed by proprioceptive feedback) represents a hallmark of bodily self-awareness (Tsakiris and Haggard 2005a). In the current study, there was some evidence of greater RHI reports in the active movement condition than in the passive condition. This finding is consistent with the idea that efferent information about the movement as well as afferent information (proprioception) may contribute to body perception. The higher scores in the active movement condition may relate to the idea that, because we have implicit knowledge of (and can think about) the various sensory effects of our movement, the experience of movement is personal and felt as such (O'Regan et al 2005).

Predictive forward models operate in this manner. Before one actively moves one's arm, a motor command is issued that calculates the most appropriate or efficient movement according to the degree of sensory uncertainty and desired results. Wolpert (2007) explains that the motor system achieves this complex task through prior experience with the relational properties of one's environment and one's own sensorimotor device. Hence, the brain is able to coordinate movements according to a statistical estimation of sensory and motor effects by means of Bayesian probability theorem. O'Regan et al (2005) further posited that people are only conscious or aware of the objects on which they are going to act and actions that are actively performed. It is possible then that feelings of ownership over one's actions contribute to heightened awareness, which in turn not only increases one's attention to the movement but also registers the movement and effector of the movement as self-specifying. This could account for the greater number of RHI reports stemming from the active movement condition.

The passive movement condition was in some ways akin to the condition of visual-tactile stimulation in that both were brought about by the experimenter yet still represented a conflict between what is seen and what is felt. Furthermore, the particular pattern of tactile stimulation and movement occurred randomly (as opposed to the deliberate movement of the active condition) such that it remains unpredictable from the subject's perspective. Because of these similarities, it might have been predicted that conditions of passive movement and visual-tactile stimulation would have similar effects on body perception. However, this was not the case according to the findings. Instead, the visual-tactile condition yielded higher RHI scores in total, with especially high scores from Q1–Q3. The visual-tactile and passive condition both involved integrated sensory information. However, it is possible that the passive movement condition was less synchronised, because of random error associated with continuous movement.

Mean total scores from the active (rather than passive) movement condition and visual-tactile condition were similar and rather stronger than those from the passive condition, although there was some variability in the individual questions. More specifically, in terms of the visual-tactile condition, Q1, Q2, and Q3 yielded higher scores whereas Q4 and Q5 yielded lower scores (compared to the active condition). This finding was expected considering the relatively poor performance of Q4 and Q5 in Botvinick and Cohen (1998). This finding could relate to the relative salience of information arising from touch versus movement. The proprioceptive sense is generally processed outside of conscious awareness whereas tactile sensation automatically triggers alerting and orienting mechanisms that focus conscious attention on the source of the sensation (O'Regan et al 2005). Thus, in terms of the current study, visual-tactile stimulation, although generated by the experimenter and occurring randomly much like the passive condition, most likely commanded more attentional resources than the visual-proprioceptive information generated by movement. In order to be effective, most illusions fundamentally require sustained attention on the stimuli. Tactile stimulation and active movement not only appear to encourage alerting and orienting mechanisms but also represent highly personal and subjectively experienced sensations. The present results suggest that what seems to be driving this particular illusion is a combination of intermodal sensation and concentrated access to the effector of the illusion. Tsakiris and Haggard (2005b) would likely suggest, however, that these intermodal sensations are not only dependent on, but also constrained by, a pre-existing and coherent somatopic representation of the body. A recent study found evidence for higher-level influences on the RHI when participants perceived a virtual body as their own body (Lenggenhager et al 2007). In this study, participants also experienced a proprioceptive drift of their whole body to a location outside of their physical body boundaries. In the current study, RHI reports were likely generated by a combination of intermodal sensation and higher-level processes that mapped the realistic rubber

hand onto the conceptual representation of the hand. The nature of the interaction between bottom–up and top–down processes in the elicitation of the RHI remains to be discovered.

Interestingly the results appeared to differ according to the particular question. More specifically, Q1 on the self-report produced a significant difference between the active and passive conditions, whereas Q3 produced the lone significant difference between the passive and asynchronous conditions. The self-report total score is believed to measure the overall presence and strength of the illusion. Still, the self-report contains items that address differential aspects of the illusion. In particular, Q1 appears to relate specifically to the correlation of seen and felt movement, whereas Q3 is more closely associated with the phenomenological quality of body ownership. Participants in the active condition reported a statistically stronger agreement with Q1 than participants in the passive condition. This suggests that active movement may facilitate the correspondence of seen with felt movement (over passive movement) but does not necessarily strengthen one's identification with the rubber hand. Participants in the passive condition reported a statistically stronger agreement with Q3 than participants in the asynchronous condition. From this finding, one can infer that synchronous movement alone (whether active or passive) strengthens one's identification with the rubber hand. These findings are somewhat corroborated by Longo et al (2008), who proposed that the experience of one's own body (ie embodiment) arises from an amalgamation of several different subjective components. Some components are related to bottom-up sensory factors with immediate effects (eg proprioception and location) while others reflect top–down influences of stored representations of the body as an object (eg feelings of one's real hand being replaced by the rubber hand). These components (eg feelings of ownership versus agency) become structured in such a way to engender embodiment yet still reflect different and dissociable aspects of embodiment. These issues could be addressed in future research.

In conclusion, the present findings appear to advance the notion that body perception is associated with the detection of synchronous multisensory signals. The present findings also suggest a role of the motor command and attentional mechanisms in the misperception of false body parts.

References

- Bahrick L E, Watson J S, 1985 "Detection of intermodal proprioceptive-visual contingency as a potential basis of self-perception in infancy" *Developmental Psychology* **21** 963–973
- Botvinick M, 2004 "Probing the neural basis of body ownership" *Science* **305** 782–783
- Botvinick M, Cohen J, 1998 "Rubber hands 'feel' touch that eyes see" *Nature* **391** 756
- Costantini M, Haggard P, 2008 "The rubber hand illusion: Sensitivity and reference frame for body ownership" *Consciousness and Cognition* **16** 229–240
- Ehrsson H H, Holmes N P, Passingham R E, 2005 "Touching a rubber hand: Feeling of body ownership is associated with activity in multisensory brain areas" *Journal of Neuroscience* **25**(45) 10564–10573
- Eimer M, 2004 "Multisensory integration: How visual experience shapes spatial perception" *Current Biology* **14** R115–R117
- Ernst M O, Banks M S, 2002 "Humans integrated visual and haptic information in a statistically optimal fashion" *Nature* **415**(6870) 429–433
- Feiner K, 1987 "Development of the concept of anatomical constancy: Part 1" *Psychoanalytic Psychology* **4** 343–354
- Gallagher S, 2000 "Self-reference and schizophrenia: A cognitive model of immunity to error through misidentification", in *Exploring the Self: Philosophical and Psychopathological Perspectives on Self-Experience* Ed. D Zahavi (Amsterdam, PA: John Benjamins) pp 203–239
- Graziano M S, 1999 "Where is my arm? The relative role of vision and proprioception in the neuronal representation of limb position" *Proceedings of the National Academy of Sciences of the USA* **96** 10418–10421
- Hiraki K, 2006 "Detecting contingency: A key to understanding development of self and social cognition" *Japanese Psychological Research* **48**(3) 204–212

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- Lenggenhager B, Tadi T, Metzinger T, Blanke O, 2007 "Video ergo sum: manipulating bodily self-consciousness" *Science* **317** 1096–1099
- Longo M R, Schuur F, Kammers M P M, Tsakiris M, Haggard P, 2008 "What is embodiment? A psychometric approach" *Cognition* **107** 978–998
- Miyazaki M, Hiraki K, 2006 "Delayed intermodal contingency affects young children's recognition of their current self" *Child Development* **77**(3) 736–750
- O'Regan N K, Myin E, Noe A, 2005 "Sensory consciousness explained (better) in terms of 'corporality' and 'alerting capacity'" *Phenomenology and Cognitive Sciences* **4**(4) 369–387
- Rochat P, 1998 "Self-perception and action in infancy" *Experimental Brain Research* **123** 102–109
- Roessler J, Eilan N (Eds), 2003 *Agency and Self-Awareness* (Oxford: Oxford University Press)
- Rorden C, Heutink J, Greenfield E, Robertson I H, 1999 "When a rubber hand 'feels' what the real hand cannot" *NeuroReport* **10** 135–138
- Tsakiris M, Haggard P, 2003 "Awareness of somatic events following a voluntary action" *Experimental Brain Research* **149** 439–446
- Tsakiris M, Haggard P, 2005a "Experimenting with the acting self" *Cognitive Neuropsychology* **22**(3/4) 387–407
- Tsakiris M, Haggard P, 2005b "The rubber hand illusion revisited: visuotactile integration and self-attribution" *Journal of Experimental Psychology: Human Perception and Performance* **31** 80–91
- Tsakiris M, Haggard P, Franck N, Mainy N, Sirigu A, 2005 "A specific role for efferent information in self-recognition" *Cognition* **96** 215–231
- Tsakiris M, Prabhu G, Haggard P, 2006 "Having a body versus moving your body: How agency structures body-ownership" *Consciousness and Cognition* **15** 423–432
- Van den Bos E, Jeannerod M, 2002 "Sense of body and sense of action both contribute to self-recognition" *Cognition* **85** 177–187
- Wolpert D M, 2007 "Probabilistic models in human sensorimotor control" *Human Movement Science* **26** 511–524

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