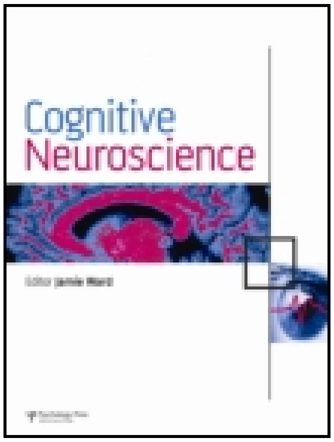

Cognitive Neuroscience
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pcns20

Imagined paralysis impairs embodied spatial transformations

Matthias Hartmann [a] , Caroline J. Falconer [a] & Fred W. Mast [a]
[a] Department of Psychology , Muesmattstrasse 45, University of Bern , Bern, Switzerland
Accepted author version posted online: 11 Aug 2011.Published online: 22 Aug 2011.

Psychology Press
Taylor & Francis Group

Imagined paralysis impairs embodied spatial transformations

Matthias Hartmann, Caroline J. Falconer, and Fred W. Mast

Department of Psychology, Muesmattstrasse 45, University of Bern, Bern, Switzerland

Recent studies showed that motor deficits and limb amputations selectively impair mental rotation of respective body parts. This is due to modifications in the body schema, which plays a pivotal role in bodily related mental spatial transformations. In the present study, we investigated whether imagined paralysis could affect mental transformations in healthy participants. Participants were required to make leg laterality judgments of imitable and non-imitable body postures that were presented at different orientations. Mental spatial transformation of imitable body posture relies on emulation processes, a mechanism through which the posture is covertly imitated by the observer. Imagined paralysis selectively impaired mental transformation of imitable body postures. These results reflect an inability to fully emulate stimulus postures, suggesting a modulation in the body schema. Our results show that the body schema incorporates top-down information about motoric constraints which can influence embodied cognition in healthy participants.

Keywords: Embodiment; Imagery; Body schema; Mental transformation; Paralysis.

Metaphors are often used to facilitate abstract thinking. A specific form of metaphor is embodiment, a process through which abstract ideas are identified with a physical entity, namely the body (MacLachlan, 2004). Embodiment is a key cognitive component involved in some mental spatial transformation abilities. For example, to determine the handedness of a person who is writing, a mental representation of one's own body can be mentally aligned to match the physical composition of that person. A paradigm that is often used to investigate embodied spatial transformations requires participants to make laterality judgments of line drawings of human bodies or body parts (Parsons, 1987a, 1987b). Amorim, Isableu, and Jarraya (2006) have shown that performance in mental transformation tasks improves with increasing body-likeness of the stimuli. The authors distinguish between two types of embodiment processes. Spatial embodiment is the process of projecting and aligning our own body axes (front–back, top–bottom, left–right) to match those of the visual stimulus. Motoric embodiment refers to the engagement of the motor system covertly emulating the stimulus posture during mental body transformations (e.g., Grush, 2004; Parsons, 1994). This process is supported by findings that show partly overlapping brain activation when observing, imagining, or physically executing a body movement (e.g., Buccino et al., 2001; Decety & Grezes, 2006; Decety & Ingvar, 1990; Urgesi et al., 2010; Vogt, 1996).

Both embodiment processes rely on a mental representation of the body—the body schema (Head & Holmes, 1911–1912). The body schema is a multisensory construct that continuously updates the status of the body in space (Gallagher, 2005). The body schema

Correspondence should be addressed to: Matthias Hartmann, Department of Psychology, Muesmattstrasse 45, CH-3012 Bern, Switzerland. E-mail: matthias.hartmann@psy.unibe.ch

The study was funded by the Swiss National Science Foundation (Pro*Doc grant PDFMP1_127238 and Sinergia grant CRSII1-125135/1). We would like to thank Damaris Bachmann, Cora Bobst, and Nora Preuss for assistance in data collection.

www.psypress.com/cognitiveneuroscience http://dx.doi.org/10.1080/17588928.2011.594498

has long been conceived as a mere "body map," but recent studies have added to a more plastic, action-oriented construct (e.g., Berlucchi & Aglioti, 2010; Longo, Azanon, & Haggard, 2010; Maravita, Spence, & Driver, 2003). Investigations of tool use in humans and monkeys have shown that tools extending our physical boundaries can become incorporated into the body schema (see Maravita & Iriki, 2004, for a review). In contrast to body schema extension, there is also evidence for disintegration of body parts. Investigations with patients suffering from motor deficits due to hand dystonia (Fiorio, Tinazzi, & Aglioti, 2006; Fiorio et al., 2007) or body part amputation (Nico, Daprati, Rigal, Parsons, & Sirigu, 2004) suggest that the representation of the affected body part diminishes in the body schema. Nico et al. (2004) found that patients with upper limb amputation have difficulty in judging rotated hand stimuli as left or right. Furthermore, studies with healthy participants have shown that the actual body posture can influence the mental transformation of bodies or body parts (de Lange, Helmich, & Toni, 2006; Funk, Brugger, & Wilkening, 2005; Ionta & Blanke, 2009; Ionta, Fourkas, Fiorio, & Aglioti, 2007; Shenton, Schwoebel, & Coslett, 2004). These studies all suggest that the body schema relies on online integration of bottom-up proprioceptive signals. In this study, we investigate whether the body schema can be influenced by top-down processes via mental imagery in healthy participants. Mental imagery has been efficiently used to improve motor performance (Lotze & Halsband, 2006), muscle relaxation, and pain (e.g., Morone & Greco, 2007; Weydert et al., 2006). Specifically, we want to study whether the mental transformation of bodies could be influenced by an imagined immobility of one's own legs. Healthy participants were instructed to imagine themselves as paralyzed from the waist down while conducting leg laterality judgments of whole-body stimuli expressing imitable or non-imitable postures. Previous studies suggested that imitable postures and non-imitable postures are processed differently (Candidi, Urgesi, Ionta, & Aglioti, 2008; Cross, Mackie, Wolford, & de C. Hamilton, 2010). Amorim et al. (2006) suggested that imitable postures can be easily embodied, as the motor system can fully emulate the depicted posture. This is not the case for non-imitable postures. If imagined paralysis influences the body schema, we would expect an impairment of embodiment, at the stage of emulation, and consequently diminished performance in the mental transformation of imitable postures. Emulation processes cannot be applied successfully for non-imitable postures and, therefore, we would not expect effects of imagined paralysis. In a control task, participants were asked to perform spatial judgments on rotated objects. No embodiment processes are involved in spatial transformation of objects. We therefore expect no effect of imagined paralysis for the control task.

METHOD

Participants

Forty-four undergraduate students participated in this study (nine male, three left-handed). The mean age was 24.5, ranging from 19 to 36. They received course credit for their participation. The study was approved by the ethics committee of the University of Bern and participants gave informed consent.

Visual stimuli

For the laterality judgment task, photographs of six different people (three male and three female) demonstrating a yoga-like posture were used as stimuli. All actors had one leg in a straight position while the other leg was bent (see Figure 1 for an example). In order to enable motoric embodiment processes, we chose

Figure 1. Example of an imitable (left) and non-imitable (right) body posture. All six actors took a similar posture.

postures that were easily imitable. For each of the six postures, we created a non-imitable version by changing a body part into a biomechanically impossible position, thus preventing full emulation (Amorim et al., 2006). Including a mirrored version of all imitable and non-imitable postures resulted in a total of 24 different body stimuli. In addition to the laterality judgment task, we used a control task that required spatial judgments of objects. For this task, letters (R, F, L) and numbers (2, 5, 7) were used as stimuli. The original and mirrored version of each object resulted in 12 different object stimuli. For all stimuli (body and object), the size was approximately 15 cm presented on a 17-inch computer screen. Each stimulus was rotated in the picture plane at five angles of rotation (0°, 45°, 90°, 135°, 180°).

Task and procedure

The experiment consisted of a body block (120 trials) and an object block (60 trials). The body block contained a short break after half of the trials were completed. Each participant performed both blocks under two different conditions: a paralysis imagery condition and a control condition. In the paralysis imagery condition, participants were instructed to imagine themselves as paralyzed from the waist down and not to move their legs. In order to emphasize the idea of being paralyzed, participants were seated on a wheelchair. Before starting a stimulus block, the experimenter carefully pushed them around an obstacle positioned in the middle of the room. Participants remained seated on the wheelchair throughout the experiment in order to help to maintain the imagery state. In the control condition, no imagery instructions were given, and participants were asked to walk around the obstacle before sitting in a normal chair and starting a stimulus block. The true purpose of the study was concealed by a cover story. At the beginning of the experiment, participants were told that the purpose of this study was to investigate a possible influence of imagined paralysis on time estimation. They were instructed to remember how much time had elapsed since the beginning of a specific time point and, when required, to report a time estimation. Time estimations were collected at the end of each stimulus block. Participants were instructed to sit still during the experiment. The order of the two conditions was counterbalanced across participants, and a short break separated the two sessions. In addition, the order of the stimulus blocks (body and object) was counterbalanced across participants. Within the blocks, stimuli were presented in random order. In order to assess the effectiveness of the paralysis instruction, a subgroup of the participants ($n = 8$) were asked to fill out a questionnaire after the experiment. They had to read statements pertaining to the ownership and awareness of their legs and arms, and rate on a 7-point Likert scale the extent to which they agreed with these statements. The questionnaire was completed after the imagery and the control condition (see Table 1).

Participants were seated in front of a computer screen at a distance of approximately 60 cm. Task

TABLE 1
Subjective reports about legs and arms during paralysis imagery and control condition

	M (SD)	
Question	*Paralysis imagery*	*Control*
Legs		
During the experiment, my legs felt useless.	4.63 (1.85)	1.38 (0.52)
My legs felt heavy during the experiment.	4.88 (1.77)	1.25 (0.46)
During the experiment, I had the impression that I could not use my legs as well as I'm used to.	5.13 (1.25)	1.13 (0.35)
During the experiment, my legs felt weak.	5.13 (1.64)	1.00 (0.00)
During the experiment, my legs felt strange, as if they did not belong to my body.	3.13 (1.96)	1.00 (0.00)
During the experiment, my legs felt paralyzed.	3.63 (0.92)	1.00 (0.00)
During the experiment, I had the impression that I could not have moved my legs if I had wanted to.	3.25 (1.28)	1.13 (0.35)
It was difficult to stand up when the experiment was finished.	3.88 (1.89)	1.00 (0.00)
Mean leg score	**4.20 (0.69)**	**1.11 (0.18)**
Arms		
During the experiment, I had the impression that I could no longer move my arms.	1.63 (0.74)	1.00 (0.00)
During the experiment, my arms felt paralyzed.	1.13 (0.35)	1.00 (0.00)
During the experiment, my arms felt strange, as if they did not belong to my body.	1.13 (0.35)	1.00 (0.00)
During the experiment, my arms felt useless.	1.25 (0.71)	1.25 (0.46)
My arms felt heavy during the experiment.	2.25 (1.28)	1.38 (0.74)
During the experiment, I had the impression that I could not use my arms as well as I'm used to.	1.63 (1.06)	1.13 (0.35)
During the experiment, my arms felt weak.	1.63 (1.41)	1.00 (0.00)
Mean arm score	**1.52 (0.80)**	**1.12 (0.15)**

Notes: Values indicate mean scores on a 7-point Likert scale where 1 means strongly disagree and 7 means strongly agree ($n = 8$).

instructions appeared on the screen prior to each stimulus block. In the body block, participants were asked to judge, as accurately and as quickly as possible, whether the bent leg was left or right in origin. In the object block, participants were asked to judge, as accurately and as quickly as possible, whether the object appeared in its original or mirror-image form. Participants responded by pressing a left or right key with the index finger of the left or right hand. A central fixation cross was presented on the screen for 300 ms, followed by the stimulus that remained until the participant responded. Each response was followed by a blank screen of 700 ms. For each task, 10 practice trials were provided. Practice trials were not identical to the stimuli in the stimulus blocks. We used Superlab 4 Software (Cedrus Corporation, San Pedro, CA) for stimulus presentation and response collection.

Data analysis

The mean response time (RT) and error rate (ER) were calculated for each participant for the different stimulus categories, angle of rotation, and condition. Two participants were excluded from further analysis because of high ERs (58% and 46%; more than 3 *SD* above the mean ER). For the analysis of RTs, data were log transformed to normalize their distribution (Ratcliff, 1993). Incorrect trials (11.02% of all trials) and RTs more than 2.5 *SD* below or above the mean of each stimulus category and rotation angle (1.31% of all trials) were excluded from the analysis. RTs and ERs were analyzed for the laterality judgment task and the control task by means of separate repeated-measures analyses of variance (ANOVA). For the laterality judgment task, the analysis included the variables condition (paralysis imagery vs. control), posture (imitable vs. non-imitable), and angle of rotation (0°, 45°, 90°, 135°, 180°). For the control task, the analysis included the variables condition (paralysis imagery vs. control) and angle of rotation (0°, 45°, 90°, 135°, 180°). Statistical analysis was performed using PASW Statistics 18 (SPSS Inc., Chicago, IL). All post hoc tests were Bonferroni-corrected.

RESULTS

Laterality judgment task

RTs and ERs for each angle of rotation and condition are illustrated in Figure 2. The analysis of log RTs revealed a significant main effect of posture, $F(1, 41) = 40.50$, $MSE = 0.005$, $p < .001$, and a significant interaction between posture and condition, $F(1, 41) = 6.20$, $MSE = 0.002$, $p = .017$. RTs for imitable postures were lower than for non-imitable postures ($M = 1447$, $SD = 732$ vs. $M = 1577$, $SD = 855$),

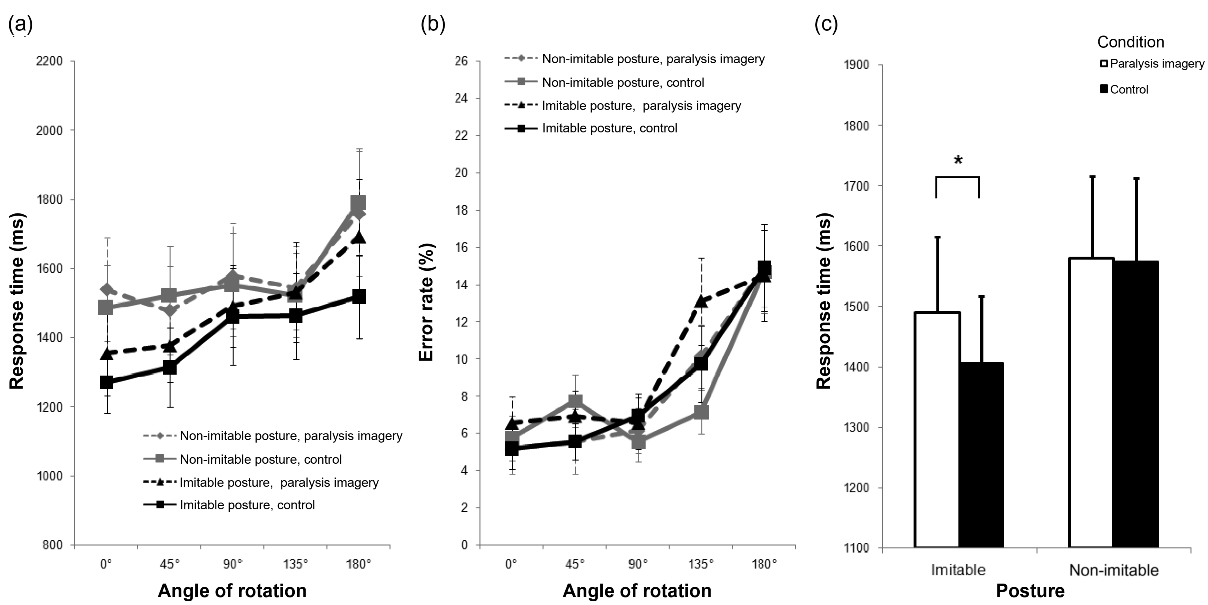

Figure 2. Mean response times (a) and error rates (b) for the laterality judgment task. Black lines represent imitable, and grey lines non-imitable body posture. Means are displayed at each angle of rotation during paralysis imagery condition (dotted line) and control condition (full line). Error bars indicate ±1 *SEM*. Interaction between posture and condition is illustrated in (c). Error bars indicate +1 *SEM*. Asterisk indicates a significant difference between the paralysis imagery condition and the control condition for the imitable postures ($p < .05$).

and paralysis imagery differentially affected these two types of stimuli. Post hoc tests revealed that imagined paralysis significantly increased RTs for the mental transformation of imitable postures, but no such effect was found for non-imitable postures (see Figure 2c). Moreover, the angle of rotation influenced RTs, $F(4, 164) = 21.83$, $MSE = 0.005$, $p < .001$. Correct spatial judgments required more time with increasing angle of rotation (see Figure 2a). Angle of rotation also interacted with posture, $F(4, 164) = 3.12$, $MSE = 0.002$, $p = .017$. Post hoc tests showed a significant difference between imitable and non-imitable postures for the rotation angles 0°, 45°, and 180°. All other effects or interactions were not significant ($p > .36$).[1] The analysis of ERs showed a main effect of angle of rotation, $F(4, 164) = 17.03$, $MSE = 2.00$, $p < .001$ (see Figure 2b). All other main effects or interactions were not significant ($p > .14$).

Object task

RTs and ERs for each angle of rotation and condition are illustrated in Figure 3. Analysis of log RTs revealed no difference between paralysis imagery and control condition, $F(1, 41) = 0.64$, $MSE = 0.013$. There was a significant effect only for angle of rotation, $F(4, 164) = 100.83$, $MSE = 0.006$, $p < .001$. Correct spatial judgements required more time with increasing angle of rotation (see Figure 3a). Analysis of ERs showed a main effect of degree of rotation, $F(4, 164) = 18.57$, $MSE = 2.578$, $p < .001$ (see Figure 3b). All other effects or interactions were not significant ($p > .85$).

[1]Some studies report laterality effects as a function of handedness for mental spatial transformation of body parts (e.g., Nico et al., 2004). To investigate possible effects of laterality in the present data, the same analysis of RTs was performed with the additional between-variable laterality of the bent leg (left vs. right). This analysis shows that right-handed participants needed less time for correct judgments when the right leg was bent ($M = 1397$ ms, $SD = 579$ ms) as compared to the left leg ($M = 1427$ ms, $SD = 580$ ms), $F(1, 38) = 4.27$, $MSE = 0.009$, $p = .046$. This supports the observation by Nico et al. (2004) that participants use a strategy in which they initially mentally simulate movements of their dominant limb, which is the right leg in most right-handed people (Brown & Taylor, 1988). Laterality of the bent leg also interacted with angle of rotation, $F(4, 152) = 3.16$, $MSE = 0.005$, $p = .016$. Post hoc test showed that the difference between the left and right leg was significant only for 0°. All other interactions with laterality of the bent leg were not significant ($p > .12$). The small number of left-handed participants in our sample ($n = 3$) does not permit conclusions about the effect of handedness of the participants.

Subjective reports and time estimations

The results of the subjective reports are shown in Table 1. Leg and arm scores were averaged for each participant and condition. The averaged scores were compared for both conditions by means of paired t-tests. During paralysis imagery, participants indicated significantly higher scores for the leg as compared to control condition, 4.20 vs. 1.12, $t(7) = 12.45$, $p < .001$. No significant difference between conditions was found for arm scores, 1.52 vs. 1.11, $t(7) = 1.38$, $p = .21$. This analysis shows that the paralysis imagery instruction had an effect on the subjective feeling of the participant's legs during the experiment.

The time estimations that were collected for the purpose of the cover story were averaged for each participant and condition. The duration of elapsed time was slightly overestimated in the paralysis imagery ($M = 12$ s, $SD = 79$ s) as well as in the control condition ($M = 15$ s, $SD = 108$ s). Paired t-tests showed no difference between the conditions, $t(41) = 0.31$, $p = .76$.

DISCUSSION

We examined whether imagined paralysis influences performance during mental spatial transformations of imitable and non-imitable body postures, and of objects. We found that leg laterality judgments of imitable body postures required more time during imagined paralysis as compared to the control condition. For postures that were not imitable, and for the object task, no effect of paralysis imagery was found. This shows that paralysis imagery exerted a selective influence on the processing of imitable body postures.

In order to correctly judge the laterality of body parts, participants imagine their own body in the orientation of the viewed posture (Parsons, 1994). If the posture was physically impossible to adopt, participants required in general more time for the laterality judgment. This shows that kinetic properties and biomechanical constraints are taken into consideration during mental spatial transformation (Overney & Blanke, 2009; Petit & Harris, 2005). The fact that there was no difference in ERs between imitable and non-imitable postures demonstrates that participants are able to solve the task with impossible postures (see also Craske, 1977; Moseley & Brugger, 2009; Romani, Cesari, Urgesi, Facchini, & Aglioti, 2005), but it demands more time. Interestingly, only imitable postures permitting full emulation were influenced by paralysis imagery. For non-imitable postures, where the emulation process is already impaired, performance during paralysis imagery

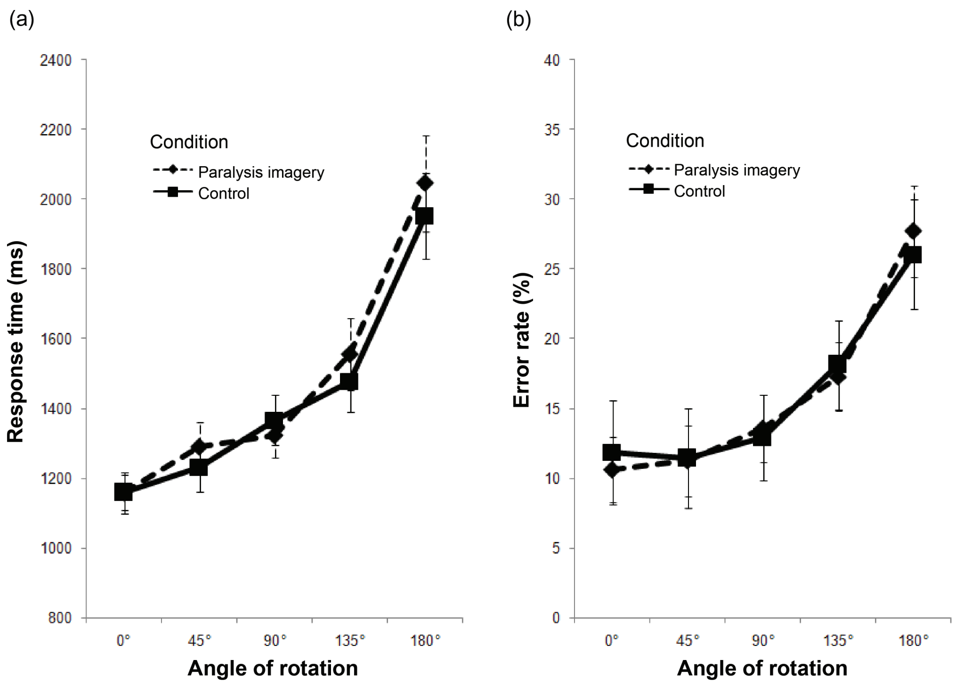

Figure 3. Mean response time (a) and error rate (b) for the control task. Means are displayed at each angle of rotation during paralysis imagery condition (dotted line) and control condition (full line). Error bars indicate ±1 *SEM*.

did not differ from the control condition. Our results suggest that paralysis imagery modulated the representation of the body, and this in turn impaired emulation processes during mental transformation of imitable postures. Imagined paralysis in healthy participants affected mental spatial transformations of the body in a way that is consistent with real motor deficits (Fiorio et al., 2006, 2007) or limb amputation (Nico et al., 2004). Therefore, these results extend our knowledge about the plasticity of the body schema by showing that some form of disintegration of body parts can be induced via top-down processes in healthy participants.

A frontoparietal network is involved in mental transformation of body stimuli (Creem et al., 2001; Vallar et al., 1999; Wraga, Shephard, Church, Inati, & Kosslyn, 2005; Zaehle et al., 2007). Patient studies have shown that lesions of this network, including the posterior parietal lobe (Overney & Blanke, 2009) and premotor cortex (Arzy, Overney, Landis, & Blanke, 2006), result in asomatognosia symptoms—the transient feeling that a body part has disappeared. Interestingly, these patients are impaired in mental transformations specific to body-related stimuli. The right insula is also associated with asomatognosia symptoms, and this brain area could be a core structure in maintaining a sense of limb ownership and awareness (Baier & Karnath, 2008; Karnath & Baier, 2010), as well as a coherent body representation (Karnath & Baier, 2010). There is also some evidence that the insula is involved in egocentric mental transformations (Wraga et al., 2005). Furthermore, some individuals deny the ownership of one or more healthy limbs and have a strong desire for amputation of that limb (apotemnophilia). This unusual disorder is characterized by disturbances in the integration of multisensory signals pertaining to the respective limb (Blanke, Morgenthaler, Brugger, & Overney, 2009; Hilti & Brugger, 2010) and even an exclusion of the limb from the body schema (Brang, McGeoch, & Ramachandran, 2008). Preliminary findings suggest that the right parietal lobe is the source of such alterations in corporeal awareness and ownership (Blanke et al., 2009; Brang et al., 2008; McGeoch et al., 2009). In light of the above, the premotor cortex, insula, and parietal areas are the prime candidates underlying the results we obtained in this study. On the one hand, lesions in these areas give rise to deficits in a coherent body representation; on the other hand, these areas are implicated in mental transformation of the body.

Modifying the body schema via mental imagery could be a promising approach for the treatment of clinical disorders involving dysfunctional body representations. For example, patients suffering from conversion paralysis are unable to perform voluntary motions despite the absence of motor deficits (de Vignemont, 2008). These patients also show selective motor imagery impairments for their affected limb (de Lange, Toni, & Roelofs, 2010). It has been suggested that conversion paralysis could result from an inability to form a "mental image" of movements (for a review, see Vuilleumier, 2005). For these patients, mental imagery or hypnotic instruction about their own corporeal awareness and motion potential could be used to improve motor performance. It would also be interesting to investigate whether it is possible to reduce symptoms in patients with asomatognosia, or people with a desire for amputation by modulating their body representation via mental imagery. An additional future study could also investigate whether imagined paralysis is accompanied by physiological changes in the "affected" limb. Moseley et al. (2008) demonstrated that altered body representation induced by conflicting visual-tactile input decreased skin temperature in the real hand.

To conclude, earlier studies have shown that modifying the body schema via bottom-up stimuli can influence the ability to mentally transform bodies or body parts (Ionta et al., 2007; Shenton et al., 2004). Our study is the first to highlight the influence of top-down information via mental imagery on the body schema and embodiment processes in healthy participants. The results demonstrate that the body schema is not a purely sensory-driven construct but is cognitively malleable via top-down processes (see also Moseley & Brugger, 2009). Top-down processes involved in one's own motoric constraints influence the body schema, and this in turn influences embodied cognition.

REFERENCES

Amorim, M. A., Isableu, B., & Jarraya, M. (2006). Embodied spatial transformations: "Body analogy" for the mental rotation of objects. *Journal of Experimental Psychology: General*, *135*(3), 327–347.

Arzy, S., Overney, L. S., Landis, T., & Blanke, O. (2006). Neural mechanisms of embodiment: Asomatognosia due to premotor cortex damage. *Archives of Neurology*, *63*(7), 1022–1025.

Baier, B., & Karnath, H. O. (2008). Tight link between our sense of limb ownership and self-awareness of actions. *Stroke*, *39*(2), 486–488.

Berlucchi, G., & Aglioti, S. M. (2010). The body in the brain revisited. *Experimental Brain Research*, *200*(1), 25–35.

Blanke, O., Morgenthaler, F. D., Brugger, P., & Overney, L. S. (2009). Preliminary evidence for a fronto-parietal dysfunction in able-bodied participants with a desire for limb amputation. *Journal of Neuropsychology*, *3*(Pt 2), 181–200.

Brang, D., McGeoch, P. D., & Ramachandran, V. S. (2008). Apotemnophilia: A neurological disorder. *Neuroreport*, *19*(13), 1305–1306.

Brown, E. R., & Taylor, P. (1988). Handedness, footedness, and eyedness. *Perceptual and Motor Skills*, *66*(1), 183–186.

Buccino, G., Binkofski, F., Fink, G. R., Fadiga, L., Fogassi, L., Gallese, V., et al. (2001). Action observation activates premotor and parietal areas in a somatotopic manner: An fMRI study. *European Journal of Neuroscience*, *13*(2), 400–404.

Candidi, M., Urgesi, C., Ionta, S., & Aglioti, S. M. (2008). Virtual lesion of ventral premotor cortex impairs visual perception of biomechanically possible but not impossible actions. *Social Neuroscience*, *3*(3–4), 388–400.

Craske, B. (1977). Perception of impossible limb positions induced by tendon vibration. *Science*, *196*(4285), 71–73.

Creem, S. H., Downs, T. H., Wraga, M., Harrington, G. S., Proffitt, D. R., & Downs, J. H., 3rd (2001). An fMRI study of imagined self-rotation. *Cognitive, Affective, & Behavioral Neuroscience*, *1*(3), 239–249.

Cross, E. S., Mackie, E. C., Wolford, G., & de C. Hamilton, A. F. (2010). Contorted and ordinary body postures in the human brain. *Experimental Brain Research*, *204*(3), 397–407.

Decety, J., & Grezes, J. (2006). The power of simulation: Imagining one's own and other's behavior. *Brain Research*, *1079*(1), 4–14.

Decety, J., & Ingvar, D. H. (1990). Brain structures participating in mental simulation of motor behavior: A neuropsychological interpretation. *Acta Psychologica*, *73*(1), 13–34.

de Lange, F. P., Helmich, R. C., & Toni, I. (2006). Posture influences motor imagery: An fMRI study. *NeuroImage*, *33*(2), 609–617.

de Lange, F. P., Toni, I., & Roelofs, K. (2010). Altered connectivity between prefrontal and sensorimotor cortex in conversion paralysis. *Neuropsychologia*, *48*(6), 1782–1788.

de Vignemont, F. (2008). Hysterical conversion: The reverse of anosognosia? In T. Bayne & J. Fernandez (Eds.), *Delusions and self-deception: Affective influences on belief-formation* (pp. 243–262). Hove, UK: Psychology Press.

Fiorio, M., Tinazzi, M., & Aglioti, S. M. (2006). Selective impairment of hand mental rotation in patients with focal hand dystonia. *Brain*, *129*(Pt 1), 47–54.

Fiorio, M., Tinazzi, M., Ionta, S., Fiaschi, A., Moretto, G., Edwards, M. J., et al. (2007). Mental rotation of body parts and non-corporeal objects in patients with idiopathic cervical dystonia. *Neuropsychologia*, *45*(10), 2346–2354.

Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental Science*, *8*(5), 402–408.

Gallagher, S. (2005). *How the body shapes the mind*. New York, NY: Oxford University Press.

Grush, R. (2004). The emulation theory of representation: Motor control, imagery, and perception. *Behavioral and Brain Sciences*, *27*(3), 377–396.

Head, H., & Holmes, G. (1911–1912). Sensory disturbances from cerebral lesions. *Brain*, *34*, 102–254.

Hilti, L. M., & Brugger, P. (2010). Incarnation and animation: Physical versus representational deficits of body integrity. *Experimental Brain Research*, *204*(3), 315–326.

Ionta, S., & Blanke, O. (2009). Differential influence of hands posture on mental rotation of hands and feet in left and right handers. *Experimental Brain Research*, *195*(2), 207–217.

Ionta, S., Fourkas, A. D., Fiorio, M., & Aglioti, S. M. (2007). The influence of hands posture on mental

rotation of hands and feet. *Experimental Brain Research*, *183*(1), 1–7.
Karnath, H. O., & Baier, B. (2010). Right insula for our sense of limb ownership and self-awareness of actions. *Brain Structure & Function*, *214*(5–6), 411–417.
Longo, M. R., Azanon, E., & Haggard, P. (2010). More than skin deep: Body representation beyond primary somatosensory cortex. *Neuropsychologia*, *48*(3), 655–668.
Lotze, M., & Halsband, U. (2006). Motor imagery. *Journal of Physiology*, *99*(4–6), 386–395.
MacLachlan, M. (2004). *Embodiment: Clinical, critical and cultural perspectives on health and illness*. Maidenhead, UK: Open University Press.
Maravita, A., & Iriki, A. (2004). Tools for the body (schema). *Trends in Cognitive Sciences*, *8*(2), 79–86.
Maravita, A., Spence, C., & Driver, J. (2003). Multisensory integration and the body schema: Close to hand and within reach. *Current Biology*, *13*(13), R531–539.
McGeoch, P. D., Brang, D., Song, T., Lee, R. R., Huang, M., & Ramachandran, V. S. (2009). Apotemnophilia — the neurological basis of a ‘psychological’ disorder. *Nature Procedings*, hdl:10101/npre.12009.12954.10101.
Morone, N. E., & Greco, C. M. (2007). Mind—body interventions for chronic pain in older adults: A structured review. *Pain Medicine*, *8*(4), 359–375.
Moseley, G. L., & Brugger, P. (2009). Interdependence of movement and anatomy persists when amputees learn a physiologically impossible movement of their phantom limb. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(44), 18798–18802.
Moseley, G. L., Olthof, N., Venema, A., Don, S., Wijers, M., Gallace, A., et al. (2008). Psychologically induced cooling of a specific body part caused by the illusory ownership of an artificial counterpart. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(35), 13169–13173.
Nico, D., Daprati, E., Rigal, F., Parsons, L., & Sirigu, A. (2004). Left and right hand recognition in upper limb amputees. *Brain*, *127*, 120–132.
Overney, L. S., & Blanke, O. (2009). Impaired imagery for upper limbs. *Brain Topography*, *22*(1), 27–43.
Parsons, L. M. (1987a). Imagined spatial transformation of one’s body. *Journal of Experimental Psychology*: *General*, *116*(2), 172–191.
Parsons, L. M. (1987b). Imagined spatial transformations of one’s hands and feet. *Cognitive Psychology*, *19*(2), 178–241.
Parsons, L. M. (1994). Temporal and kinematic properties of motor behavior reflected in mentally simulated action. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(4), 709–730.
Petit, L. S., & Harris, I. M. (2005). Anatomical limitations in mental transformations of body parts. *Visual Cognition*, *12*(5), 737–758.
Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin*, *114*(3), 510–532.
Romani, M., Cesari, P., Urgesi, C., Facchini, S., & Aglioti, S. M. (2005). Motor facilitation of the human corticospinal system during observation of bio-mechanically impossible movements. *NeuroImage*, *26*(3), 755–763.
Shenton, J. T., Schwoebel, J., & Coslett, H. B. (2004). Mental motor imagery and the body schema: Evidence for proprioceptive dominance. *Neuroscience Letters*, *370*(1), 19–24.
Urgesi, C., Maieron, M., Avenanti, A., Tidoni, E., Fabbro, F., & Aglioti, S. M. (2010). Simulating the future of actions in the human corticospinal system. *Cerebral Cortex*, *20* (11), 2511–2521.
Vallar, G., Lobel, E., Galati, G., Berthoz, A., Pizzamiglio, L., & Le Bihan, D. (1999). A fronto-parietal system for computing the egocentric spatial frame of reference in humans. *Experimental Brain Research*, *124*(3), 281–286.
Vogt, S. (1996). Imagery and perception-action mediation in imitative actions. *Cognitive Brain Research*, *3*(2), 79–86.
Vuilleumier, P. (2005). Hysterical conversion and brain function. *Progress in Brain Research*, *150*, 309–329.
Weydert, J. A., Shapiro, D. E., Acra, S. A., Monheim, C. J., Chambers, A. S., & Ball, T. M. (2006). Evaluation of guided imagery as treatment for recurrent abdominal pain in children: A randomized controlled trial. *BMC Pediatrics*, *6*, 29.
Wraga, M., Shephard, J. M., Church, J. A., Inati, S., & Kosslyn, S. M. (2005). Imagined rotations of self versus objects: An fMRI study. *Neuropsychologia*, *43*(9), 1351–1361.
Zaehle, T., Jordan, K., Wustenberg, T., Baudewig, J., Dechent, P., & Mast, F. W. (2007). The neural basis of the egocentric and allocentric spatial frame of reference. *Brain Research*, *1137*(1), 92–103.