Faulty proprioceptive information disrupts motor imagery: an experimental study

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Question: Does faulty proprioceptive input disrupt the internal model of the body that the brain uses to control movement? ***Design:*** Randomised, within-participant experimental study. ***Participants:*** Twenty-two (13 F) healthy adults. ***Intervention:*** Participants performed a motor imagery task that involved making left/right judgements of pictured right and left hands in 16 different postures under five conditions involving stimuli being applied to the experimental (L) hand. The five conditions were: vibration (of the wrist extensor tendons to elicit the illusion of wrist flexion), sham (vibration of the ulna styloid), active flexion, passive flexion, and control (no stimulus). ***Outcome measures:*** Accuracy and response time of the control (R) hand in making left/right judgements of the pictures. ***Results:*** Response time during vibration was longer for those who reported the illusion of wrist flexion (n = 18) than for those who did not ($p < 0.01$) whereas accuracy was unaffected ($p = 0.71$). In those who reported the illusion, accuracy was unaffected by condition, hand or picture ($p > 0.21$). Response time during vibration was 910 ms longer (95% CI 730 to 1090) for pictures of the experimental (L) hand (mean 2731 ms, 95% CI 2543 to 2918) than it was for pictures of the control (R) hand (mean 1822 ms, 95% CI 1634 to 2009), and ~ 580 ms longer (95% CI 380 to 785) for pictures of either hand during any other condition ($p <0.025$). ***Conclusion:*** Faulty proprioceptive input disrupted this motor imagery task, which suggests it can disrupt the model of the limb that the brain uses for movement. **[McCormick K, Zalucki N, Hudson ML, Moseley GL (2007) Faulty proprioceptive information disrupts motor imagery: an experimental study *Australian Journal of Physiotherapy* 53: 41–45]**

Keys words: Proprioception, Complex Regional Pain Syndromes, Motor activity, Pain

Introduction

It has been argued that faulty proprioceptive input is a cause of pain in health conditions such as phantom limb pain (Flor et al 2001, Flor et al 2006, Harris 1999, Ramachandran 2005, Ramachandran et al 1995) and complex regional pain syndrome (Harris 1999, McCabe et al 2005, McCabe et al 2003). The theoretical model proposes that faulty proprioceptive input disrupts the internal representation of the limb. Because the internal representations of the body are the models the brain uses to control the musculoskeletal system, their disruption is thought to cause incongruence between motor output and sensory feedback. It is proposed that pain serves as a warning system to alert the individual to this incongruence (Harris 1999) (see McCabe et al 2005 for review). This theory has been investigated (McCabe et al 2005, Moseley and Gandevia 2005, Moseley et al 2006) but fundamental questions remain.

One question is whether faulty proprioceptive information directly disrupts the models the brain uses for movement. Answering this question requires measurement of motor processes but not motor performance, because the latter would be confounded by the impact of the proprioceptive disturbance on the motor command at spinal and tissue levels. The hand laterality recognition task satisfies this requirement because it involves motor imagery but not movement. In the hand laterality recognition task, participants are shown pictures of hands and are required to determine whether each hand is a left hand or a right hand. To do this, one makes an initial 'automatic' judgement and then confirms that judgement by mentally moving one's own hand to match the posture of the hand shown in the picture (Parsons 2001). Because the task depends on motor imagery, more awkward pictures take longer to recognise (Moseley 2004b, Parsons 1987, Parsons and Fox 1998, Sekiyama 1982).

The hand laterality recognition task is also relevant here because, in painful conditions, the response is delayed if the pictured hand coincides with the participant's painful limb (Moseley 2004b, Moseley 2006b, Nico et al 2004, Schwoebel et al 2002, Schwoebel et al 2001). The explanation proposed for this delay is consistent with that proposed for the pain of these conditions – that faulty proprioceptive input disrupts the model of the limb that the brain uses for movement (Nico et al 2004).

The research question for this study was:

1. Does faulty proprioceptive input disrupt the internal model of the body that the brain uses to control movement?

To determine this, proprioceptive feedback was disrupted experimentally by applying medium-frequency vibration to the tendons on one wrist to induce the perception that the limb was moving. This illusion is thought to be caused by stimulation of muscle spindles, which results in faulty

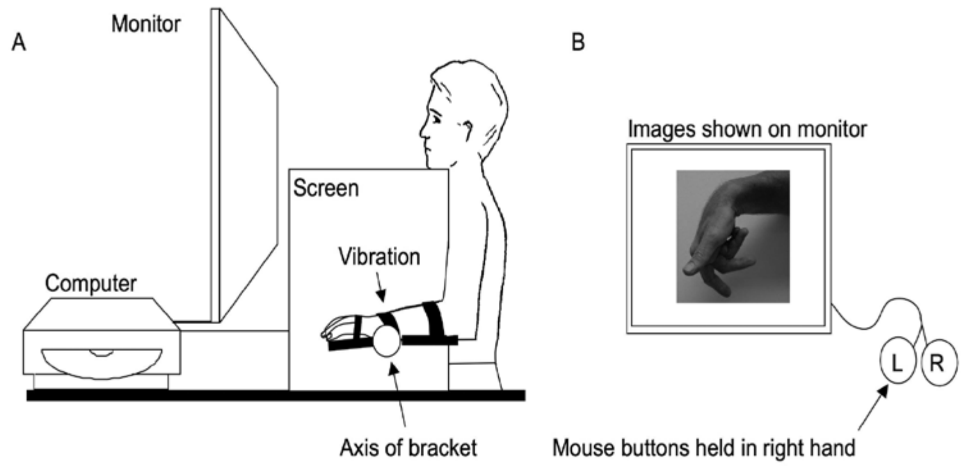

Figure 1. Experimental set-up for the hand laterality recognition task. (A) The left hand and forearm were held in a bracket, obscured from the sitting participant by a screen. Vibration was applied to the extensor tendons at the left wrist. (B) The participant responded as quickly as possible to a photograph of a hand, by pressing with the right hand, one of two buttons according to whether the photograph showed a left or a right hand. Buttons were placed under the second and third digit of the right hand.

proprioceptive information being sent to the brain (Lackner 1988). Therefore, perception of the illusion was assumed to be evidence of disrupted proprioceptive input. The primary hypothesis was that when participants experienced illusory wrist movement, response time would be longer for pictures of the experimental hand than for pictures of the control hand.

Method

Design: This study was a randomised within-participant experimental study. Participants performed a motor imagery task that involved making left/right judgements of pictured hands under different conditions. Sixteen pictures of a right hand in various postures (see Fig. 3) were digitally mirrored to provide 16 identical pictures of a left hand. The 32 pictures were randomly presented twice each on a monitor in front of the sitting participant using MATLAB 6.5[(a)]. With a computer mouse held in their right hand, participants responded to each picture by pressing the left mouse button with their index finger if they thought the picture showed a left hand, and the right mouse button with their middle finger if they thought the picture showed a right hand (Fig. 1). There was a period of two seconds between the response to one picture and presentation of the next. There were two practices of the 64 pictures that were not analysed. This motor imagery task was performed under five conditions, undertaken in random order, with at least 5 minutes break between each condition. Therefore, data were collected for right/left judgements of 320 pictures from each participant. Emphasis was placed on responding as quickly as possible but without making mistakes. This study conformed to the Declaration of Helsinki and was approved by the ethics committees of The University of Queensland and Royal Brisbane and Women's Hospital. Written informed consent was obtained from all participants.

Participants: Healthy adults were invited to participate.

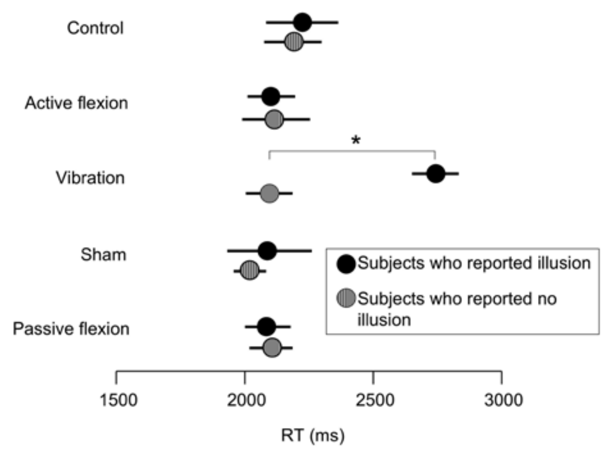

Figure 2. Effect of illusion of movement on response time (RT) for each condition. Mean (circles) and SE (error bars) response time to recognise the laterality of photographs of the experimental hand in participants that reported the illusion (filled circles) and those who reported no illusion during vibration (shaded circles). Asterisk shows that response time was longer during the vibration condition ($p < 0.01$) for participants who reported the illusion of wrist movement than it was for participants who reported no illusion.

Hand dominance, age, and gender were not exclusion criteria because those variables do not affect performance at the hand laterality recognition task used here (Hudson et al 2006, Moseley 2004b, Moseley et al 2005). Participants who on questioning reported that they had current pain or had had an episode of unilateral arm or hand pain less than three months beforehand, or that they had dyslexia, were excluded.

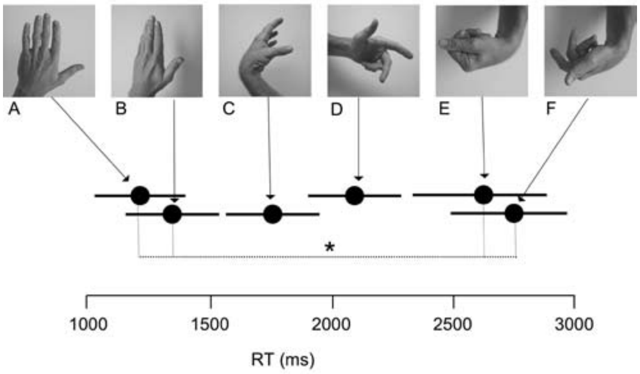

Figure 3: Effect of picture on response time (RT) across conditions. Mean (circles) and SD (error bars) response time to recognise the laterality of pictured hands for selected pictures, which shows the relationship between the awkwardness of the pictured hand's posture and the response time to recognise its laterality. Asterisk shows that response time for pictures E and F were longer than response time for pictures A and B ($p < 0.05$).

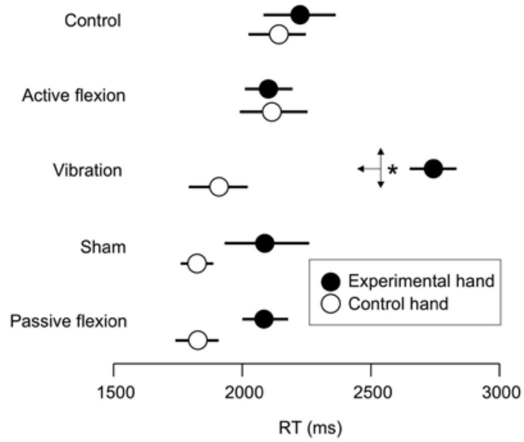

Figure 4: Effect of hand on response time (RT) for each condition for participants who reported the illusion of wrist movement during tendon vibration. Mean (circles) and SE (error bars) of response time for pictures of the experimental (L) hand (filled circles) and the control (R) hand (empty circles). Asterisk shows (i) that response time for pictures of the experimental hand was longer than response time for pictures of the control hand during vibration and (ii) that response time for pictures of the experimental hand was longer during vibration than it was during any other condition ($p < 0.01$).

Intervention: The motor imagery task was performed under five conditions: vibration to the extensor tendons of the wrist (*Vibration*), vibration to the ulnar styloid (*Sham*), wrist held actively in flexion (end of active range – 20°) (*Active flexion*), wrist held passively in flexion by a bracket (*Passive flexion*), and wrist in neutral with no bracket (*Control*). An in-house vibrator (70 Hz) was used. Due to technical limitations of the set-up, all stimuli were applied to the left hand, which was held in a bracket behind a screen. The right hand was placed in a similar position, but not out of sight. Thus, the left hand was the experimental hand and the right hand was the control hand.

Outcome measures: Accuracy of left/right judgements was measured as the number of correct responses as a proportion of total responses. Response time was measured as the time in ms for correct responses.

Data analysis: A sample size of 22 was sufficient to detect a difference on the laterality recognition task of 600 ms (Moseley 2004b), with a probability of ≥ 80%, assuming $\alpha = 0.05$. Response time data were skewed, so they were log-transformed for all statistical analyses. A Mann-Whitney test for two unrelated samples compared accuracy and response time of left/right judgements during the vibration condition between those who reported the illusion of wrist flexion and those who reported no illusion of wrist movement. Only data from participants who reported the illusion were included in the next analyses. To compare the effect of condition, hand and picture on response time, we undertook a three-factor ANOVA. The first factor was *Condition* which had five levels: vibration, sham vibration, active flexion, passive flexion, and control. The second factor was *Hand* which had two levels: left and right. The third factor was *Picture* which had 16 levels because there were 16 postures. Although *Picture* increased the degrees of freedom, we included it in this ANOVA to verify that our protocol was sufficiently sensitive to detect the known effect of the awkwardness of a pictured posture on response time. We undertook a two-factor (*Condition*, *Hand*) ANOVA on accuracy of left/right judgements, which is not vulnerable to the awkwardness of a pictured posture (Parsons 2001). Correction for multiple comparisons was applied such that significance was set at $\propto = 0.025$.

Results

Participants Twenty-two healthy adults aged 29 years (SD 9) participated. Thirteen participants were female and two were left handed. Four participants did not perceive the illusion of wrist movement.

Effect of illusion of movement on accuracy and response time of left/right judgements: Mean accuracy of left/right judgements was 91% (SD 5) for those who reported the illusion of wrist flexion and 90% (SD 7) for those who did not. Both groups were accurate across conditions and there was no difference between groups ($p = 0.71$).

Response time for pictures of the experimental (L) hand was 307 ms longer for those who reported an illusion than for those who did not ($p < 0.01$). There was no difference in response time between hands in any of the other conditions ($p > 0.03$ for all) (Fig. 2).

Effect of condition, hand and picture on accuracy and response time of left/right judgements: Mean accuracy for pictures of the experimental (L) hand ranged from 88% (SD 5) during the active flexion condition to 92% (SD 6) during the sham condition. Neither *Condition* nor *Hand* affected accuracy ($F_{(4,11)} = 0.70$, $p = 0.61$ for *Condition*; $F_{(1,14)} = 0.18$, $p = 0.68$ for *Hand*; $F_{(4,11)} = 1.04$, $p = 0.43$ for *Condition* × *Hand* interaction).

Response times for pictures that involved a large rotation in three planes to adopt the posture from the participant's resting position were longer than response times for pictures that involved little or no rotation (main effect of *Picture* on response time ($F_{(15, 2714)} = 6.85$, $p < 0.001$, post-hoc $p < 0.01$) (Fig. 3). Neither *Condition* nor *Hand* affected response time. However, response time during vibration was 910 ms longer (95% CI 730 to 1090) for pictures of the experimental (L) hand (mean 2731 ms, 95% CI 2543 to 2918) than it was for pictures of the control (R) hand (mean 1822 ms, 95% CI 1634 to 2009). Response time during vibration was ~ 580 ms longer (95% CI 380 to 785) for pictures of either hand during any other condition (*Condition* × *Hand* interaction ($F_{(4, 2714)} = 6.79$, $p < 0.001$; post-hoc $p < 0.025$ for all) (Fig. 4). There was no difference between response time for pictures of the experimental (L) hand and response time for pictures of the control (R) hand during any other condition, nor were there differences in response time for pictures of the control hand between any of the conditions ($p > 0.69$ for all).

Discussion

The hypothesis that response time would be longer for pictures of the experimental hand but not for pictures of the control hand when participants experienced the illusion of movement was upheld. That there was no effect of illusion or condition on accuracy of responses suggests that participants did not alter their strategy for the task and that the effect is not simply the result of an accuracy-response time trade-off. The current findings demonstrate that faulty proprioceptive input can disrupt the model of the body that the brain uses for movement.

The current data are consistent with studies of left/right judgements in asymptomatic volunteers (Hudson et al 2006, Moseley 2004b, Parsons 2001) that demonstrate similar accuracy and response times. The data obtained during vibration are similar to those observed for pictures of the affected limb in patients with complex regional pain syndrome (Moseley 2004b) and patients with phantom limb pain (Moseley 2006b, Nico et al. 2004). The validity of the data is upheld by the relationship between the response time to recognise the laterality of pictured hands and the awkwardness of the posture shown in the picture. In short, response time correlates with the degree of rotation and excursion that would be required to move the participant's own hand from its resting posture to the posture shown in the picture (Moseley 2004b, Parsons 2001). This principle is demonstrated in part by Figure 3.

That faulty proprioceptive input can disrupt the internal model of the limb that the brain uses for movement substantiates one aspect of the sensory-motor incongruence theory. This is important because the theory underpins clinical strategies that are gaining popularity, eg, mirror therapy for phantom limb pain, complex regional pain syndrome, and stroke rehabilitation (Berthelot 2006, Karmarkar and Lieberman 2006, McCabe et al 2003, Murray et al 2006). Because strong evidence of clinical effectiveness is not yet available, these strategies depend on their theoretical rationale. If the rationale is unsubstantiated, then the treatments are open to criticism. This study substantiates one aspect of the sensory-motor incongruence theory, although it does not prove the theory, nor directly support the clinical strategies based upon it. Two other aspects of the sensory-motor incongruence theory are that much of our conscious awareness of limb movements depends on predicted feedback rather than actual feedback (Frith et al 2000) and that error between predicted and actual feedback is monitored closely within the motor control system (Von Holst 1950). There is a large amount of evidence for these arguments (see Gandevia 1996 for review). The sensory-motor incongruence theory combines the latter notion of error detection with the former notion of conscious awareness to propose that in challenged systems (eg, in complex regional pain syndrome), detection of the predicted-actual feedback error evokes a protective conscious response – which is pain (McCabe et al 2005). There are data that seem consistent with that, but other data that do not (see Moseley 2006 for a review).

The delay evoked by illusory wrist movement was almost one second. Such a long delay would obviously have profound effects on movement performance and therefore on function. However, it should be remembered that the delay was evoked here by disrupting proprioceptive input in a very artificial manner. The extent of the delay is not the important finding; it is the fact that a motor imagery task can be delayed in this way that is important.

Because judging limb laterality depends not only on motor imagery, but also on initial information processing (Parsons 2001), it is possible that the effect observed here may have involved an interruption of information processing. Acute pain and expectation of acute pain probably affect limb laterality recognition via an effect on information processing (Hudson et al 2006), although the direction of that effect is opposite to that observed here. This is important because the current effect would require an information processing bias away from the experimental hand, whereas, using a spatial attention paradigm, non-noxious stimuli have been shown to have the opposite effect (Van Damme et al 2004). Furthermore, if vibration does affect information processing, so should sham vibration – which did not. Another potential issue is that illusory movement activates supplementary motor and premotor cortices (Naito et al 1999). That raises the possibility that the delay occurs because the brain is trying to do two things at once. The current paradigm attempted to control for that by including an active flexion condition, which did not affect response time.

Three methodological issues of the current study should be noted. First, the left hand was always the experimental hand and the sample included left-handers. There is no effect of dominance of the pictured or response hands using this task (Hudson et al 2006, Moseley 2004a, Moseley 2004b, Moseley 2005, Moseley 2006a, Moseley 2006b, Moseley et al 2005) but it remains possible that vibration has a differential effect on each hand, in which case the current data may not be generalisable to the right hand. Second, that the experimental hand was hidden from view and the control hand was not could have increased the time to recognise images of the experimental hand, although one would expect an effect of *Hand* across all conditions. Randomising which hand is stimulated and whether it is visible would clarify these two issues. Finally, the study may have been underpowered to detect other, potentially important effects. For example, response time may be reduced for the control hand during passive flexion ($p = 0.04$). Such a decrease in response time is difficult to explain and warrants further investigation.

In conclusion, faulty proprioceptive input can disrupt motor imagery. This effect probably involves disruption of the model of the limb that the brain uses for movement. This finding substantiates one aspect of the sensory-motor incongruence theory but neither supports, nor refutes, the theory itself.

Footnotes: [(a)]Release 13, The MathWorks Inc, Natick, MA, USA

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References

Berthelot JM (2006) Current management of reflex sympathetic dystrophy syndrome (complex regional pain syndrome type 1). *Joint Bone Spine* 73: 495–499.

Flor H, Denke C, Schaefer M, Grusser S (2001) Effect of sensory discrimination training on cortical reorganisation and phantom limb pain. *Lancet* 357: 1763–1764.

Flor H, Nikolajsen L, Jensen TS (2006) Phantom limb pain: a case of maladaptive CNS plasticity? *Nature Reviews Neuroscience* 7: 873–881.

Frith CD, Blakemore SJ, Wolpert DM (2000) Abnormalities in the awareness and control of action. *Philosophical Transcripts of the Royal Society London* 355: 1771–1788.

Gandevia S (1996) Kinesthesia: roles for afferent signals and motor commands. In Rothwell L, Shepherd J (Eds) Handbook of Physiology. New York: Oxford University Press, pp. 128–172.

Harris AJ (1999) Cortical origin of pathological pain. *Lancet* 354: 1464–1466.

Hudson ML, McCormick K, Zalucki N, Moseley GL (2006) Expectation of pain replicates the effect of pain in a hand laterality recognition task: Bias in information processing toward the painful side? *European Journal of Pain* 10: 219–224.

Karmarkar A, Lieberman I (2006) Mirror box therapy for complex regional pain syndrome. *Anaesthesia* 61: 412–413.

Lackner J (1988) Some proprioceptive influences on the perceptual representation of body shape and orientation. *Brain* 111: 281–297.

McCabe CS, Haigh RC, Halligan PW, Blake DR (2005) Simulating sensory-motor incongruence in healthy volunteers: implications for a cortical model of pain. *Rheumatology* 44: 509–516.

McCabe CS, Haigh RC, Ring EFJ, Halligan PW, Wall PD, Blake DR (2003) A controlled pilot study of the utility of mirror visual feedback in the treatment of complex regional pain syndrome (type 1). *Rheumatology* 42: 97–101.

Moseley GL (2004a) Graded motor imagery is effective for long-standing complex regional pain syndrome. *Pain* 108: 192–198.

Moseley GL (2004b) Why do people with CRPS 1 take longer to recognise their affected hand? *Neurology* 62: 2182–2186.

Moseley GL (2005) Is successful rehabilitation of complex regional pain syndrome due to sustained attention to the affected limb? A randomized clinical trial. *Pain* 114: 54–61.

Moseley GL (2006a) Graded motor imagery for pathological pain. A randomized clinical trial. *Neurology* 67: 2129–2134.

Moseley GL (2006b) Making sense of s1 mania – are things really that simple? In Gifford L (Ed.) Topical issues in pain Volume 5. Falmouth: CNS Press, pp. 321–340.

Moseley GL, Gandevia SC (2005) Sensory-motor incongruence and reports of 'pain'. *Rheumatology* 44: 1083–1085.

Moseley GL, McCormick K, Hudson M, Zalucki N (2006) Disrupted cortical proprioceptive representation evokes symptoms of peculiarity, foreignness and swelling, but not pain. *Rheumatology* 45: 196–200.

Moseley GL, Sim DF, Henry ML, Souvlis T (2005) Experimental hand pain delays recognition of the contralateral hand – evidence that acute and chronic pain have opposite effects on information processing? *Cognitive Brain Research* 25: 188–194.

Murray CD, Patchick E, Pettifer S, Caillette F, Howard T (2006) Immersive virtual reality as a rehabilitative technology for phantom limb experience: a protocol. *Cyberpsychology & Behavior* 9: 167–170.

Naito E, Ehrsson HH, Geyer S, Zilles K, Roland PE (1999) Illusory arm movements activate cortical motor areas: a positron emission tomography study. *Journal of Neuroscience* 19: 6134–6144.

Nico D, Daprati E, Rigal F, Parsons L, Sirigu A (2004) Left and right hand recognition in upper limb amputees. *Brain* 127: 120–132.

Parsons LM (1987) Imagined spatial transformations of ones hands and feet. *Cognitive Psychology* 19: 178–241.

Parsons LM (2001) Integrating cognitive psychology, neurology and neuroimaging. *Acta Psychologica* 107: 155–181.

Parsons LM, Fox PT (1998) The neural basis of implicit movements used in recognising hand shape. *Cognitive Neuropsychology* 15: 583–615.

Ramachandran VS (2005) Plasticity and functional recovery in neurology. *Clinical Medicine* 5: 368–373.

Ramachandran VS, Rogers Ramachandran D, Cobb S (1995) Touching the phantom limb. *Nature* 377: 489–490.

Schwoebel J, Coslett HB, Bradt J, Friedman R, Dileo C (2002) Pain and the body schema: effects of pain severity on mental representations of movement. *Neurology* 59: 775–777.

Schwoebel J, Friedman R, Duda N, Coslett HB (2001) Pain and the body schema: evidence for peripheral effects on mental representations of movement. *Brain* 124: 2098–2104.

Sekiyama K (1982) Kinesthetic aspects of mental representation in the identification of left and right hands. *Perceptual Psychophysics* 32: 89–95.

Van Damme S, Crombez G, Eccleston C, Goubert L (2004) Impaired disengagement from threatening cues of impending pain in a crossmodal cueing paradigm. *European Journal of Pain* 8: 227–236.

Von Holst H (1950) Relations between the central nervous system and the peripheral organs. *British Journal of Animal Behaviour* 2: 89–94.