PROCEEDINGS OF THE ROYAL SOCIETY B

Proc. R. Soc. B (2010) **277**, 2503–2509
doi:10.1098/rspb.2010.0404
Published online 7 April 2010

Disrupting the experience of control in the human brain: pre-supplementary motor area contributes to the sense of agency

James W. Moore[1], Diane Ruge[2], Dorit Wenke[3,4], John Rothwell[2] and Patrick Haggard[1,*]

[1]*Institute of Cognitive Neuroscience, University College London, London WC1N 3AR, UK*
[2]*Sobell Department of Motor Neuroscience and Movement Disorders, Institute of Neurology, University College London, London WC1N 3EB, UK*
[3]*Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany*
[4]*Department of Experimental, Clinical and Health Psychology, Ghent University, Ghent, Belgium*

The feeling of controlling events through one's actions is fundamental to human experience, but its neural basis remains unclear. This 'sense of agency' (SoA) can be measured quantitatively as a temporal linkage between voluntary actions and their external effects. We investigated the brain areas underlying this aspect of action awareness by using theta-burst stimulation to locally and reversibly disrupt human brain function. Disruption of the pre-supplementary motor area (pre-SMA), a key structure for preparation and initiation of a voluntary action, was shown to reduce the temporal linkage between a voluntary key-press action and a subsequent electrocutaneous stimulus. In contrast, disruption of the sensorimotor cortex, which processes signals more directly related to action execution and sensory feedback, had no significant effect. Our results provide the first direct evidence of a pre-SMA contribution to SoA.

Keywords: voluntary action; agency; pre-supplementary motor area; sensorimotor cortex; theta-burst stimulation; transcranial magnetic stimulation

1. INTRODUCTION

The ability to plan and control actions in order to achieve desired goals is a hallmark of human and animal intelligence. In humans, at least, such operant actions also produce a characteristic conscious experience of controlling external events, called 'sense of agency' (SoA).

Several studies have sought to identify the brain circuits underlying SoA. Most have manipulated the sensory feedback associated with action, and asked subjects to explicitly judge whether they are the agent responsible for the feedback. The inferior parietal cortex is activated in these explicit attributions of agency (e.g. Chaminade & Decety 2002; Farrer & Frith 2002; Farrer *et al.* 2008). Moreover, patients with damage to the parietal cortex perform poorly on tasks where they are asked to judge whether visual feedback corresponds to their own action (Sirigu *et al.* 1999). However, parietal regions seem to be concerned more with non-agency in cases of incongruent feedback ('that was *not* me') than with the positive experience of agency itself. Furthermore, the explicit judgements of agency used in such tasks may involve different processes from the background feeling, or sense, of agency that accompanies our normal voluntary action (Synofzik *et al.* 2008).

Implicit measures provide an alternative way of quantifying SoA, and may be better suited to capturing this background feeling about one's own action (Synofzik *et al.* 2008). Such measures are implicit in that participants do not make explicit attributions or judgements of agency. A number of implicit measures of the SoA have been proposed, including the attenuation of self-produced sensations (Blakemore *et al.* 2000) and changes of time perception associated with voluntary movement. Here we focus on the latter.

When a voluntary action is followed by a sensory effect, there is subjective compression of the interval between the two events. In one paradigm, participants are asked to estimate the time of the action, or the time of a subsequent tone, in separate blocks (Haggard *et al.* 2002*b*). Actions are perceived as shifted later in time towards the tone, in comparison to a baseline condition in which subjects' actions do not produce tones. A tone that follows an action is perceived as shifted earlier towards the action that causes it, relative to a baseline condition involving tones but no actions (Haggard *et al.* 2002*a*,*b*; Tsakiris & Haggard 2003). These shifts were found for voluntary actions but not for involuntary movements (Haggard *et al.* 2002*a*,*b*) or pairings of two sensory events (Haggard *et al.* 2002*a*; Stetson *et al.* 2006), suggesting a mechanism specific to intentional action. A similar compression is found if participants judge the interval between action and tone, rather than the time of each event individually (Engbert *et al.* 2007, 2008).

We have investigated the neural substrates involved in SoA by measuring the effects of locally disrupting brain activity on this 'intentional binding' effect. We used non-invasive continuous theta-burst brain stimulation

* Author for correspondence (p.haggard@ucl.ac.uk).

Electronic supplementary material is available at http://dx.doi.org/10.1098/rspb.2010.0404 or via http://rspb.royalsocietypublishing.org.

Received 26 February 2010
Accepted 19 March 2010

(cTBS), a protocol that has consistently been shown to inhibit neural activity in the target brain region (Huang & Rothwell 2004; Huang *et al.* 2005, 2007). Two candidate brain regions were selected: the sensorimotor hand area (SMHA) and the pre-supplementary motor area (pre-SMA). The SMHA is primarily concerned with motor execution and sensorimotor feedback (e.g. Weiller *et al.* 1996), while the pre-SMA is involved in the more cognitive aspects of internal movement generation (Picard & Strick 2001) and with the conscious urge to act (Fried *et al.* 1991). In this way, both target regions are plausibly neural substrates of SoA, but are distinguishable in terms of both their function and time of contribution. Thus, any change in the intentional binding effect resulting from disrupting either one of these areas would help to identify what neural signals may underlie SoA. These disruptions can be compared with the effects of stimulation of a control site not likely to be involved in SoA, but generating the same non-specific effects of TMS, such as arousal, auditory stimulation and cutaneous stimulation. If cTBS over either pre-SMA or SMHA significantly alters binding, we may infer that the relevant brain area contributes to SoA. Further, if cTBS at both sites significantly alters binding, we may compare the deficits across the two stimulation sites to establish the relative contributions of each. However, this analysis would make sense only after showing that both areas contribute to binding.

2. MATERIAL AND METHODS

(a) *Participants*

Ten right-handed individuals (five females; mean age 25.20 years) took part with the approval of the National Hospital for Neurology and Neurosurgery Research Ethics Committee in three sessions on separate days. Participants were screened before entry into the experiment to ensure they showed an intentional binding effect (Haggard *et al.* 2002*a*,*b*). Of 20 participants initially screened, 16 showed significant binding for actions and 17 showed significant binding for effects. We selected the 13 participants who showed significant binding for both actions and effects (see §2*b* for details of the task). Ten of these 13 participants were recruited in the present experiment (three were unable to attend follow-up testing). The logic behind this screening is as follows: intervention to disrupt a behavioural effect can only sensibly be studied when the effect is present. Since these 10 individuals showed evidence of intentional binding, they were particularly appropriate participants in our attempt to disrupt intentional binding. By implication, our results apply to the population of participants showing intentional binding, which may not be representative of the population as a whole. Similar screening has been used in other neurophysiological studies of motor representation (e.g. Wolters *et al.* 2003; Stefan *et al.* 2006). The presence of the binding effect within a wider, unscreened population was established in previous studies (Haggard *et al.* 2002*a*,*b*).

(b) *Procedure: behavioural test*

Behavioural testing occurred immediately after cTBS (see §2*c* for details) and followed previous methods (e.g. Haggard *et al.* 2002*a*,*b*; see also figure 1*a* for set-up). Participants were instructed to press a key with their right index finger at a time of their choosing. This caused a cutaneous somatosensory stimulus (a mild shock) to the right little finger 250 ms later in agency conditions, but not in baseline conditions. Whereas previous studies used an auditory tone as the effect of action (e.g. Moore & Haggard 2008), we chose to use a somatosensory stimulus in this case, so that the key signals for both action and the effects of action would be co-localized in a single brain area (the SMHA). This increased the likelihood of disrupting neural processing of both action and effect signals.

While making actions and receiving shocks, participants viewed a clock hand rotating with a period of 2560 ms. Following the action and shock delivery, the clock hand continued rotating for a random period of time. After the clock stopped, the participant verbally reported the position of the clock hand at which they pressed the key, or the time at which they felt the shock. Action judgements and shock judgements were performed in separate blocks of trials. In two further baseline blocks, participants made actions but never received shocks, or received shocks at a random time but never made actions. Each block contained 20 trials. Block order was randomized anew for each session (see below). Testing lasted approximately 15 min, well within the window of cTBS efficacy (Huang *et al.* 2005).

Prior to each session, each participant's detection threshold for cutaneous shocks from ring electrodes on the right little finger (one ring electrode placed on the proximal phalanx and the other on the middle phalanx) was identified by an ascending staircase procedure. Shock intensity was varied by changing pulse width until the shock was detected, then decreased with half the step size until the shock was missed and then increased again with further halving of the step size, until the fourth reversal of responding (Levitt 1971). The average of the final two reversals was taken as the detection threshold. The experimental shocks used 140 per cent of each participant's detection threshold for that session.

(c) *Neurophysiological methods*

Subjects sat comfortably in a reclining chair. Surface electromyography was recorded from the first dorsal interosseous (FDI) muscle of the right hand using 9 mm diameter Ag–AgCl surface electrodes in a belly-tendon montage. The active electrode was placed over the belly muscle, and the reference electrode over the metacarpophalangeal joint of the index finger. Responses were amplified, filtered with a 20 Hz–2 kHz passband and digitally sampled at 5 kHz.

A Super Rapid Magstim package (Magstim Co., Whitland, Dyfedd, UK) was connected to a 70 mm figure-of-eight coil. To stimulate the primary motor cortex, the coil was placed tangentially to the skull with the handle pointing backwards and rotated 45° away from the midline. The optimal coil position ('hotspot') for activating the contralateral FDI was determined as the site where stimulation at a slightly suprathreshold stimulus intensity consistently produced the largest motor-evoked potential (MEP). We then calculated the active motor threshold (AMT) at this hotspot by asking the participant to maintain a slight isometric contraction (5–10% of maximum voluntary contraction) and identifying the lowest stimulus intensity that elicited a mean MEP >200 μV from at least five of ten consecutive trials (Rossini *et al.* 1994).

Theta-burst stimulation (TBS) consists of repeating bursts of TMS, with three pulses at 50 Hz repeated at 200 ms intervals (i.e. at 5 Hz). A train of 600 pulses, termed continuous theta-burst stimulation, can suppress

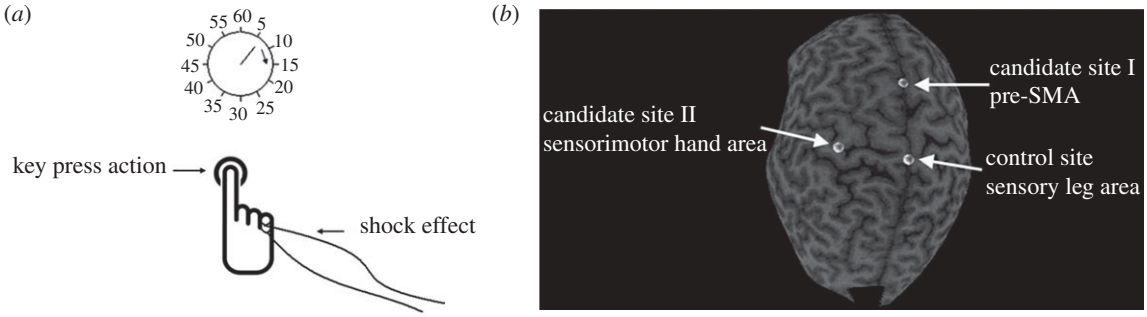

Figure 1. (*a*) Experimental set-up used in the study. See text for details. (*b*) Putative sites of cTBS stimulation (based on neuro-navigation in a separate group of three participants).

local cortical excitability for approximately 20–30 min (Huang *et al.* 2005). Stimulation intensity was set to 80 per cent of the AMT for the FDI muscle at the motor cortex hotspot. All participants had cTBS stimulation at three stimulation sites (SMHA, pre-SMA, S1-leg area) in separate sessions in a random order. Participants were not informed of the specific stimulation site at each session. No adverse consequences of cTBS occurred. For SMHA stimulation, the optimal stimulation site to evoke MEPs in the FDI muscle was used. To target the pre-SMA, a site 4 cm anterior to the hotspot of the FDI was marked in the sagittal midline (Cz of the international 10-20-EEG system) of the scalp (Rushworth *et al.* 2002; Mars *et al.* 2009). In one participant, bilateral twitches in the leg muscles were evoked at this location by high stimulation intensity (90% maximal stimulator output). The coil was then moved 0.5 cm more anteriorly so that twitches no longer occurred. To target the S1-leg area as a control site, a position 2 cm posterior to the hot spot for the FDI muscle in the sagittal midline of the skull was marked on the scalp.

The location of the scalp stimulation sites with respect to the underlying brain anatomy was examined with TMS-MRI co-registration in a separate group of three subjects. The three stimulation positions used in the main experiment were identified in the same way as for the experimental subjects and marked on each subject's scalp. A high-resolution three-dimensional volumetric structural magnetic resonance image (MRI) was obtained for each subject. The cortical surface was displayed as a three-dimensional representation using BRAINSIGHT FRAMELESS stereotaxic software (Rogue Research, Montreal, Quebec, Canada). Each stimulation site was identified on the MRI image using a pointer tool (BRAINSIGHT FRAMELESS P-697), while the position of the pointer and the subject's head were monitored using a Polaris Optical Tracking system (Northern Digital, Waterloo, Ontario, Canada). One example is shown in figure 1*b*. The anatomical location of the pre-SMA was identified from the border between the SMA proper and the pre-SMA, which is defined by the plane perpendicular to the anterior commissure–posterior commissure (AC–PC) line at the level of the AC (Picard & Strick 1996). We could confirm in all three subjects that the site of TMS stimulation on the scalp lay over the anatomically defined pre-SMA in the brain.

The order of testing sessions was counterbalanced using the Latin square procedure. All three of each participant's testing sessions took place at a similar time of day (either am or pm) to minimize circadian effects. The order of perceptual judgement blocks was randomized anew for each session.

(d) *Data analysis*

The perceived time of action or shock on each trial was compared with the actual onset time, and a mean temporal error calculated for each block. The mean error for actions and shocks in baseline blocks was subtracted from that in experimental blocks. Subtracting these baseline estimates allowed us to calculate the shift in the perceived time of the action when the shock was present and the shift in the perceived time of the shock when caused by the action. These shifts serve as measures of 'intentional binding' between action and effect. By convention, a positive temporal shift indicates delayed awareness. Therefore, a positive shift for actions represents binding of actions towards shocks, while a negative shift for shocks represents binding of shocks towards the preceding action. Finally, an overall measure of binding between action and effect was calculated as action binding minus tone binding. Larger values of this measure indicate stronger action-effect binding. All data are presented in electronic supplementary material, table S1.

(e) *Controlling for possible cTBS-induced changes in sensory intensity*

cTBS could, in principle, alter somatosensory function, leading to changes in the perceived time of shock stimuli. To control for this possibility, we additionally checked whether cTBS affected perceived shock intensity, which could in turn affect timing judgements.

Therefore, before each cTBS session, subjects received five 'reference shocks', triggered by their own key press, and at the same intensity as in the main experiment. They were asked to attend to the intensity of these reference shocks for subsequent comparison. After each block of trials (except the baseline action condition in which there were no shocks), participants were asked to compare the shock intensity they experienced during the block with the initial reference shocks, using a seven-point scale ($-3 =$ experimental shocks much less intense than reference; $+3 =$ experimental shocks much more intense). These ratings were averaged across the blocks in each to give a total measure of perceived shock intensity following stimulation at each TMS site (electronic supplementary material, table S1).

3. RESULTS

The experience of intentionally controlling shocks changed the perceived time of both action and shock. Overall binding between action and effect is measured by the action shift minus the effect shift (figure 2). If SoA depends on brain circuits for internal generation of action, then overall

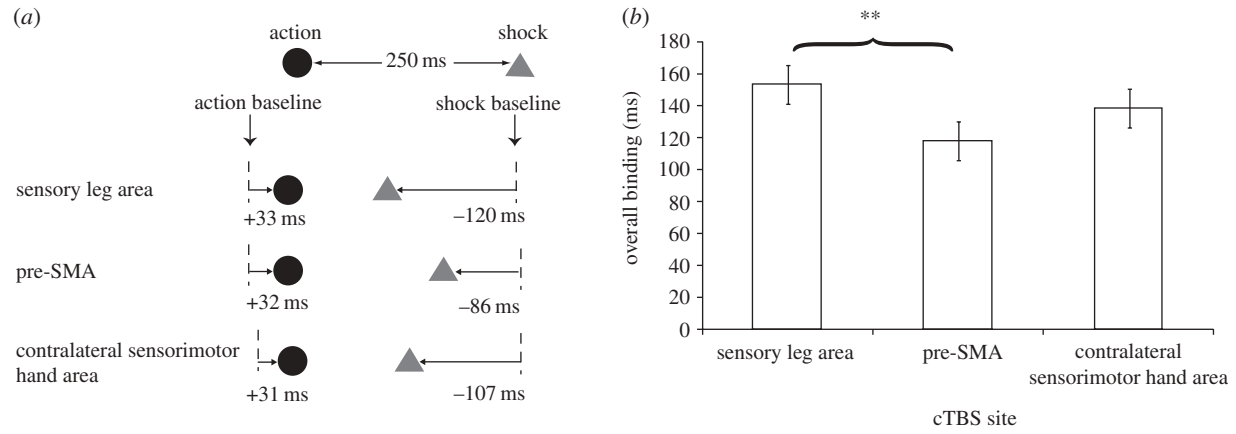

Figure 2. (*a*) Upper row: in experimental conditions, actions were followed by shocks 250 ms later. Lower three rows: changes in the perceived time of actions and effects following cTBS in each condition. Black circles indicate the mean perceived time of actions, dashed vertical lines indicate the baseline judgements of actions in that session. Grey triangles indicate the mean perceived time of shocks, and dashed vertical lines indicate baseline shock judgements in that session. Numbers indicate the size of the shift in ms. Note the reduced binding following pre-SMA cTBS. (*b*) Mean overall binding between action and effect (action shift minus shock shift) in ms for each site of stimulation. Bars represent standard error of the mean across participants. $^{**}p < 0.01$.

binding following pre-SMA stimulation should be reduced relative to control stimulation. Alternatively, if SoA depends on brain circuits for action execution and somatosensory feedback, then overall binding following SMHA stimulation should be reduced relative to control. Because both areas might make independent contributions, we made no prediction about the difference between pre-SMA and SMHA stimulations.

Pre-SMA stimulation indeed reduced the overall amount of binding (118 ± 22 ms s.e.) relative to control stimulation of the sensory leg area (153 ± 24 ms s.e.; two-tailed paired samples *t*-test: $t(9) = 3.49$, $p = 0.007$). Testing each shift separately showed that pre-SMA stimulation influenced the shift in the perceived time of the effect (two-tailed paired samples *t*-test: $t(9) = 2.32$, $p = 0.045$), but not the shift in action (two-tailed paired samples *t*-test: $t(9) = 0.058$, $p = 960$). Interestingly, the effect of stimulation on our composite binding measure is statistically stronger than that on action binding or effect binding individually. This pattern was found because pre-SMA stimulation influenced primarily action binding for some subjects, and effect binding for others. However, the implied interval between action and effect was influenced with much greater reliability than either event individually.

SMHA stimulation had a much smaller influence on overall binding (137 ± 31 ms s.e.). Moreover, this influence was rather variable across individuals, and did not differ significantly from control stimulation over the sensory leg area (two-tailed paired samples *t*-test: $t(9) = 0.469$, $p = 0.650$). Testing each shift separately revealed that SMHA stimulation did not significantly affect either action binding (two-tailed paired samples *t*-test: $t(9) = 0.119$, $p = 0.911$) or effect binding (two-tailed paired samples *t*-test: $t(9) = 0.758$, $p = 0.468$). Since we found no reliable evidence that the SMHA was involved in binding, we could not proceed to directly compare the magnitudes of the two disruptions (§1).

We also investigated whether cTBS might affect time perception generally by comparing baseline judgements across the different stimulation conditions. Baseline judgements of both actions and effects were unaffected by pre-SMA stimulation relative to control site (two-tailed paired samples *t*-test: baseline action, $t(9) = 0.095$, $p = 0.926$; baseline tone, $t(9) = 0.710$, $p = 0.496$). Equally, SMHA stimulation produced no change in baseline judgements relative to control site (two-tailed paired samples *t*-test: baseline action, $t(9) = 0.582$, $p = 0.575$; baseline tone, $t(9) = 0.246$, $p = 0.811$). Therefore, it seems unlikely that our results are merely an artefact of poor time perception, or similar non-specific factors.

Finally, we investigated whether cTBS might have affected perceived shock intensity, perhaps leading to differences in perceived timing. We found no differences in perceived intensity between control (S1-leg area) and pre-SMA stimulation (two-tailed paired samples *t*-test: $t(9) = 0.483$, $p = 0.641$), nor between control and SMHA stimulation (two-tailed paired samples *t*-test: $t(9) = 1.41$, $p = 0.193$; see electronic supplementary material, table S1, for data). This suggests that TMS-induced changes in perceptual timing are unlikely to be due to changes in perceived intensity.

4. DISCUSSION

In this study, we used cTBS to shed light on the neural substrate of SoA. Two candidate brain regions were stimulated: pre-SMA and SMHA. The effects of stimulating each area on intentional binding (a temporal measure of SoA) were compared with the stimulation of a control area (sensory leg area). Following pre-SMA disruption, we found significant reduction in overall intentional binding, and particularly in the binding of sensory consequences towards actions. Disruption of the SMHA with cTBS did not significantly reduce binding relative to the control area.

(a) *Limitations*

We have used an indirect measure of agency based on time perception. In contrast, previous studies investigated explicit judgements of agency (Farrer & Frith 2002). Intentional binding is a useful measure of SoA to the extent that it occurs only in situations that indeed involve

agency—that is, when a self-generated movement produces a sensory effect, but not when involuntary movements lead to the same effects (Haggard *et al.* 2002*a*,*b*), nor where two stimuli co-occur without a voluntary action (Haggard *et al.* 2002*a*; Stetson *et al.* 2006). However, it remains unclear whether intentional binding, and SoA, *always* accompanies *all* self-generated movements. Several studies suggest that binding (Moore *et al.* 2009*b*; Ebert & Wegner 2010) and action experience in general (Haggard *et al.* 2004) can be influenced by contextual factors and suggestions about one's action.

Many studies of voluntary action, including this one, have focused on the pre-SMA (Fried *et al.* 1991). Our pre-SMA localization followed that used successfully in previous studies (Rushworth *et al.* 2002; Mars *et al.* 2009), and was confirmed by neuronavigation in a separate group of three participants. However, a potential limitation of our study is the absence of any functional localizer confirming that our cTBS was located over the pre-SMA. Therefore, our cTBS could also have affected neighbouring regions, such as SMA-proper, so disruption there might underlie our effects. However, the relatively low stimulation intensity of 80 per cent AMT makes a contamination of other areas by current spread rather unlikely. Co-registration of our pre-SMA stimulation site, albeit in a different group of subjects, also confirmed that the coil was located anterior to SMA-proper, which was defined anatomically as being anterior to the plane perpendicular to the AC–PC line at the level of the AC.

A related concern are the possible remote effects of TMS (Bestmann *et al.* 2004). In principle, our pre-SMA results could arise from disruption to regions connected to the pre-SMA rather than in the pre-SMA itself. This possibility cannot be ruled out completely. The candidate areas for such remote effects should be strongly connected to the pre-SMA. The major input to the pre-SMA comes from the basal ganglia (BG; Akkal *et al.* 2007). The major targets of pre-SMA output are prefrontal regions (Bates & Goldman-Rakic 1993; Luppino *et al.* 1993; Johansen-Berg *et al.* 2004) and the BG (Inase *et al.* 1999; Lehéricy *et al.* 2004). However, it is unclear whether disruption of these remote areas would produce changes in SoA. A candidate prefrontal region with respect to SoA is the dorsolateral prefrontal cortex (DLPFC). The current literature gives few indications whether remote disruption of these areas could be the basis of our findings. Early imaging studies showed that DLPFC activity is greater for active versus passive movements (e.g. Frith *et al.* 1991), which suggests a role in the initiation of voluntary action. However, more recent imaging research suggests that the specific function of DLFPC is in the selection between action alternatives, particularly under conflict, rather than volition *per se* (Rowe *et al.* 2000). In our study, participants made only one action, so action selection was absent. This reduces the putative influence of DLPFC. The BG are another possible source of remote effects of pre-SMA stimulation. Here, it is harder to rule out remote effects. One recent study showed *intact* intentional binding in patients with Parkinson's disease (Moore *et al.* 2010). BG dysfunction in Parkinson's disease, and putative disruption of BG function by remote effects of cTBS over pre-SMA, are clearly not strictly equivalent. However, this result at least suggests that remote BG disruption is unlikely to explain our pre-SMA findings.

(b) *The pre-SMA: a premotor contribution to SoA?*

The pre-SMA plays a key role in the initiation and control of voluntary action (Deiber *et al.* 1991; Hikosaka *et al.* 1996; Nachev *et al.* 2007). Higher-order features of motor cognition have also been attributed to the pre-SMA; direct stimulation of this region produces a conscious 'urge to move' (Fried *et al.* 1991), and attending to the intention to move activates this area (Lau *et al.* 2004). Taken together, these results suggest that the pre-SMA plays a key role in the experience of volition by coding the conscious intention to move. Our results suggest that the pre-SMA may also contribute to SoA. Lasting disruption of putative pre-SMA significantly weakened a temporal marker of agency, namely the perceived association between actions and effects.

Theoretically, SoA could arise from either of two distinct processes. On the one hand, SoA may involve a prediction—based on the neural commands for action—that the sensory effect will occur. On the other hand, the brain might infer, or *postdict*, from the conjunction of action and effect (Hume 1739) that the action caused the effect, as in illusions of conscious will (Wegner 2002). Recent behavioural studies show that the intentional binding effect involves a combination of both processes. First, the binding of outcomes towards actions was significantly reduced in blocks where additional outcome events could sometimes occur in the absence of action, compared with blocks where outcomes occurred only directly after actions. This suggests that outcome binding reflects an inference based on knowledge about the distribution of outcomes (Moore *et al.* 2009*a*). Second, when the outcome following an action was occasionally omitted, a shift in perceived time of action towards the predicted tone was nevertheless observed (Moore & Haggard 2008). When *both* predictive and postdictive information are available, they may be combined in a flexible way, according to the availability and reliability of each (Moore *et al.* 2009*b*).

Distinguishing between predictive and postdictive components of SoA requires varying the conditional probabilities of tones and actions. In the present study, actions were always followed by shocks in the experimental blocks, so both prediction and postdiction could have contributed to binding. Therefore, we cannot conclusively determine whether the reduced binding effect caused by pre-SMA stimulation reflects a disruption of prediction or of postdiction. However, a predictive role is more consistent with other evidence regarding the role of the pre-SMA in action preparation. In particular, recordings from the pre-SMA have demonstrated its role both in action preparation and in anticipatory processing of warning signals prior to action (Ikeda *et al.* 1999).

We found that pre-SMA cTBS disrupted effect binding more than action binding. Recent computational models also emphasize the role of effect prediction in SoA (Blakemore *et al.* 2002). Specifically, the pre-SMA may link intentions to the sensory consequences of the intended action, a view that is consistent with ideomotor theories of voluntary action (James 1890). A previous study found that disruption of this area abolished sensory suppression during voluntary movement (Haggard & Whitford 2004). In the present study, we showed analogous effects on the linkage between action and effect. Disruption of the pre-SMA reduced the tendency to

link representations of action and effect across time. This result suggests that the pre-SMA may use motor information to generate predictions of the sensory consequences of action.

Care is needed in interpreting our SMHA results. First, there was some evidence of reduced binding following SMHA stimulation, though this was not statistically reliable. In particular, effects of SMHA stimulation were highly variable across individuals. This inter-individual variability presumably did not merely reflect poor localization of the SMHA, since objective physiological criteria were used to localize this area in each participant. Because we did not find strong evidence for any SMHA role in binding, we could not sensibly compare the contributions of the pre-SMA and SMHA to investigate which was more important. The absence of any SMHA effect in our data could be a simple statistical power limitation, given our relatively small number of participants. More research is required to confirm whether the SMHA contributes to binding.

In conclusion, we show that the subjective feeling of control, as indexed by the temporal linkage between actions and effects, depends at least partly on the pre-SMA. More specifically, we suggest that the pre-SMA makes a special contribution to SoA, housing the predictive mechanisms contributing to the SoA. These results shed light on the neural substrate of SoA and suggest a strong link between SoA, motor prediction and medial premotor cortex.

This work was supported by an ESRC/MRC studentship to J.M. D.W. was supported by an ESRC project grant to P.H. P.H. was additionally supported by a Royal Society University Research Fellowship and a Leverhulme Trust Major Research Fellowship. D.R. was supported by the Dystonia Medical Research Foundation (DMRF), Action Medical Research and the Wellington Hospital. D.R. and J.R. were supported by the Medical Research Council.

REFERENCES

Akkal, D., Dum, R. P. & Strick, P. L. 2007 Supplementary motor area and presupplementary motor area: targets of basal ganglia and cerebellar output. *J. Neurosci.* **27**, 10 659–10 673. (doi:10.1523/JNEUROSCI.3134-07.2007)

Bates, J. F. & Goldman-Rakic, P. S. 1993 Prefrontal connections of medial motor areas in the rhesus monkey. *J. Comp. Neurol.* **336**, 211–228. (doi:10.1002/cne.903360205)

Bestmann, S., Baudewig, J., Siebner, H. R., Rothwell, J. C. & Frahm, J. 2004 Functional MRI of the immediate impact of transcranial magnetic stimulation on cortical and subcortical motor circuits. *Eur. J. Neurosci.* **19**, 1950–1962. (doi:10.1111/j.1460-9568.2004.03277.x)

Blakemore, S. J., Wolpert, D. & Frith, C. 2000 Why can't you tickle yourself? *Neuroreport* **11**, R11–R16. (doi:10.1097/00001756-200008030-00002)

Blakemore, S., Wolpert, D. & Frith, C. 2002 Abnormalities in the awareness of action. *Trends Cogn. Sci.* **6**, 237–242. (doi:10.1016/S1364-6613(02)01907-1)

Chaminade, T. & Decety, J. 2002 Leader or follower? Involvement of the inferior parietal lobule in agency. *Neuroreport* **13**, 1975–1978. (doi:10.1097/00001756-200210280-00029)

Deiber, M. P., Passingham, R. E., Colebatch, J. G., Friston, K. J., Nixon, P. D. & Frackowiak, R. S. 1991 Cortical areas and the selection of movement: a study with positron emission tomography. *Exp. Brain Res.* **84**, 393–402.

Ebert, J. P. & Wegner, D. M. 2010 Time warp: authorship shapes the perceived timing of actions and events. *Conscious. Cogn.* **19**, 481–489. (doi:10.1016/j.concog.2009.10.002)

Engbert, K., Wohlschläger, A., Thomas, R. & Haggard, P. 2007 Agency, subjective time, and other minds. *J. Exp. Psychol. Hum. Percept. Perform.* **33**, 1261–1268. (doi:10.1037/0096-1523.33.6.1261)

Engbert, K., Wohlschläger, A. & Haggard, P. 2008 Who is causing what? The sense of agency is relational and efferent-triggered. *Cognition* **107**, 693–704. (doi:10.1016/j.cognition.2007.07.021)

Farrer, C. & Frith, C. D. 2002 Experiencing oneself vs another person as being the cause of an action: the neural correlates of the experience of agency. *NeuroImage* **15**, 596–603. (doi:10.1006/nimg.2001.1009)

Farrer, C., Frey, S. H., Van Horn, J. D., Tunik, E., Turk, D., Inati, S. & Grafton, S. T. 2008 The angular gyrus computes action awareness representations. *Cereb. Cortex* **18**, 254–261. (doi:10.1093/cercor/bhm050)

Fried, I., Katz, A., McCarthy, G., Sass, K. J., Williamson, P., Spencer, S. S. & Spencer, D. D. 1991 Functional organization of human supplementary motor cortex studied by electrical stimulation. *J. Neurosci.* **11**, 3656–3666.

Frith, C. D., Friston, K., Liddle, P. F. & Frackowiak, R. S. J. 1991 Willed action and the prefrontal cortex in man: a study with PET. *Proc. R. Soc. Lond. B* **244**, 241–246. (doi:10.1098/rspb.1991.0077)

Haggard, P. & Whitford, B. 2004 Supplementary motor area provides an efferent signal for sensory suppression. *Brain Res.* **19**, 52–58. (doi:10.1016/j.cogbrainres.2003.10.018)

Haggard, P., Aschersleben, G., Gehrke, J. & Prinz, W. 2002*a* Action, binding and awareness. In *Common mechanisms in perception and action*. Attention and Performance XIX (eds W. Prinz & B. Hommel). Oxford, UK: Oxford University Press.

Haggard, P., Clark, S. & Kalogeras, J. 2002*b* Voluntary action and conscious awareness. *Nat. Neurosci.* **5**, 382–385. (doi:10.1038/nn827)

Haggard, P., Cartledge, P., Dafydd, M. & Oakley, D. A. 2004 Anomalous control: when 'free-will' is not conscious. *Conscious. Cogn.* **13**, 646–654. (doi:10.1016/j.concog.2004.06.001)

Hikosaka, O., Sakai, K., Miyauchi, S., Takino, R., Sasaki, Y. & Pütz, B. 1996 Activation of human presupplementary motor area in learning of sequential procedures: a functional MRI study. *J. Neurophysiol.* **76**, 617–621.

Huang, Y. & Rothwell, J. C. 2004 The effect of short-duration bursts of high-frequency, low-intensity transcranial magnetic stimulation on the human motor cortex. *Clin. Neurophysiol.* **115**, 1069–1075. (doi:10.1016/j.clinph.2003.12.026)

Huang, Y., Edwards, M. J., Rounis, E., Bhatia, K. P. & Rothwell, J. C. 2005 Theta burst stimulation of the human motor cortex. *Neuron* **45**, 201–206. (doi:10.1016/j.neuron.2004.12.033)

Huang, Y., Chen, R., Rothwell, J. C. & Wen, H. 2007 The after-effect of human theta burst stimulation is NMDA receptor dependent. *Clin. Neurophysiol.* **118**, 1028–1032. (doi:10.1016/j.clinph.2007.01.021)

Hume, D. 1739 *A treatise of human nature*. Oxford, UK: Oxford University Press.

Ikeda, A. *et al.* 1999 Cognitive motor control in human presupplementary motor area studied by subdural recording of discrimination/selection-related potentials. *Brain* **122**, 915–931.

Inase, M., Tokuno, H., Nambu, A., Akazawa, T. & Takada, M. 1999 Corticostriatal and corticosubthalamic input zones from the presupplementary motor area in the macaque monkey: comparison with the input zones from the

supplementary motor area. *Brain Res.* **833**, 191–201. (doi:10.1016/S0006-8993(99)01531-0)

James, W. 1890 *The principles of psychology*. New York, NY: Henry Holt.

Johansen-Berg, H., Behrens, T. E. J., Robson, M. D., Drobnjak, I., Rushworth, M. F. S., Brady, J. M., Smith, S. M., Higham, D. J. & Matthews, P. M. 2004 Changes in connectivity profiles define functionally distinct regions in human medial frontal cortex. *Proc. Natl Acad. Sci. USA* **101**, 13 335–13 340. (doi:10.1073/pnas.0403743101)

Lau, H. C., Rogers, R. D., Haggard, P. & Passingham, R. E. 2004 Attention to intention. *Science* **303**, 1208–1210. (doi:10.1126/science.1090973)

Lehéricy, S., Ducros, M., Krainik, A., Francois, C., Van de Moortele, P., Ugurbil, K. & Kim, D.-S. 2004 3-D diffusion tensor axonal tracking shows distinct SMA and pre-SMA projections to the human striatum. *Cereb. Cortex* **14**, 1302–1309. (doi:10.1093/cercor/bhh091)

Levitt, H. 1971 Transformed up-down methods in psychoacoustics. *J. Acoust. Soc. Am.* **49**(Suppl. 2), 467–477. (doi:10.1121/1.1912375)

Luppino, G., Matelli, M., Camarda, R. & Rizzolatti, G. 1993 Corticocortical connections of area F3 (SMA-proper) and area F6 (pre-SMA) in the macaque monkey. *J. Comp. Neurol.* **338**, 114–140. (doi:10.1002/cne.903380109)

Mars, R. B., Klein, M. C., Neubert, F., Olivier, E., Buch, E. R., Boorman, E. D. & Rushworth, M. F. S. 2009 Short-latency influence of medial frontal cortex on primary motor cortex during action selection under conflict. *J. Neurosci.* **29**, 6926–6931. (doi:10.1523/JNEUROSCI.1396-09.2009)

Moore, J. & Haggard, P. 2008 Awareness of action: inference and prediction. *Conscious. Cogn.* **17**, 136–144. (doi:10.1016/j.concog.2006.12.004)

Moore, J. W., Lagnado, D., Deal, D. C. & Haggard, P. 2009*a* Feelings of control: contingency determines experience of action. *Cognition* **110**, 279–283. (doi:10.1016/j.cognition.2008.11.006)

Moore, J. W., Wegner, D. M. & Haggard, P. 2009*b* Modulating the sense of agency with external cues. *Conscious. Cogn.* **18**, 1056–1064. (doi:10.1016/j.concog.2009.05.004)

Moore, J. W., Schneider, S. A., Schwingenschuh, P., Moretto, G., Bhatia, K. P. & Haggard, P. 2010 Dopaminergic medication boosts action-effect binding in Parkinson's disease. *Neuropsychologia* **48**, 1125–1132. (doi:10.1016/j.neuropsychologia.2009.12.014)

Nachev, P., Wydell, H., O'neill, K., Husain, M. & Kennard, C. 2007 The role of the pre-supplementary motor area in the control of action. *NeuroImage* **36**(Suppl. 2), T155–T163. (doi:10.1016/j.neuroimage.2007.03.034)

Picard, N. & Strick, P. 1996 Motor areas of the medial wall: a review of their location and functional activation. *Cereb. Cortex* **6**, 342–353.

Picard, N. & Strick, P. L. 2001 Imaging the premotor areas. *Curr. Opin. Neurobiol.* **11**, 663–672. (doi:10.1016/S0959-4388(01)00266-5)

Rossini, P. M. *et al.* 1994 Non-invasive electrical and magnetic stimulation of the brain, spinal cord and roots: basic principles and procedures for routine clinical application. Report of an IFCN committee. *Eletroencephalogr. Clin. Neurophysiol.* **91**, 79–92. (doi:10.1016/0013-4694(94)90029-9)

Rowe, J. B., Toni, I., Josephs, O., Frackowiak, R. S. & Passingham, R. E. 2000 The prefrontal cortex: response selection or maintenance within working memory? *Science* **288**, 1656–1660. (doi:10.1126/science.288.5471.1656)

Rushworth, M., Hadland, K. A., Paus, T. & Sipila, P. K. 2002 Role of the human medial frontal cortex in task switching: a combined fMRI and TMS study. *J. Neurophysiol.* **87**, 2577–2592.

Sirigu, A., Daprati, E., Pradat-Diehl, P., Franck, N. & Jeannerod, M. 1999 Perception of self-generated movement following left parietal lesion. *Brain* **122**, 1867–1874.

Stefan, K., Wycislo, M., Gentner, R., Schramm, A., Naumann, M., Reiners, K. & Classen, J. 2006 Temporary occlusion of associative motor cortical plasticity by prior dynamic motor training. *Cereb. Cortex* **16**, 376–385. (doi:10.1093/cercor/bhi116)

Stetson, C., Cui, X., Montague, P. R. & Eagleman, D. M. 2006 Motor-sensory recalibration leads to an illusory reversal of action and sensation. *Neuron* **51**, 651–659. (doi:10.1016/j.neuron.2006.08.006)

Synofzik, M., Vosgerau, G. & Newen, A. 2008 Beyond the comparator model: a multifactorial two-step account of agency. *Conscious. Cogn.* **17**, 219–239. (doi:10.1016/j.concog.2007.03.010)

Tsakiris, M. & Haggard, P. 2003 Awareness of somatic events associated with a voluntary action. *Exp. Brain Res.* **149**, 439–446. (doi:10.1007/s00221-003-1386-8)

Wegner, D. M. 2002 *The illusion of conscious will* (illustrated edition). Cambridge, MA: MIT Press.

Weiller, C., Jüptner, M., Fellows, S., Rijntjes, M., Leonhardt, G., Kiebel, S., Müller, S., Diener, H. C. & Thilmann, A. F. 1996 Brain representation of active and passive movements. *NeuroImage* **4**, 105–110. (doi:10.1006/nimg.1996.0034)

Wolters, A., Sandbrink, F., Schlottmann, A., Kunesch, E., Stefan, K., Cohen, L. G., Benecke, R. & Classen, J. 2003 A temporally asymmetric Hebbian rule governing plasticity in the human motor cortex. *J. Neurophysiol.* **89**, 2339–2345. (doi:10.1152/jn.00900.2002)