Manipulating the Experienced Onset of Intention after Action Execution

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Abstract

■ Using transcranial magnetic stimulation (TMS), we have tested the time needed for the perceived onset of spontaneous motor intention to be fully determined. We found that TMS applied over the presupplementary motor area after the execution of a simple spontaneous action shifted the perceived onset of the motor intention backward in time, and shifted the perceived time of action execution forward in time. The size of the effect was similar regardless of whether TMS was applied immediately after the action or 200 msec after. The results of three control studies suggest that this effect is time-limited, specific to modality, and also specific to the anatomical site of stimulation. We conclude that the perceived onset of intention depends, at least in part, on neural activity that takes place after the execution of action. A model, which is based on the mechanism of cue integration under the presence of noise, is offered to explain the results. The implications for the conscious control of spontaneous actions are discussed. ■

INTRODUCTION

We experience a strong sense of conscious control when generating spontaneous, or self-paced, motor actions. This experience has been challenged as "illusory": Wegner (2002, 2003) has argued that although we perceive our motor intentions to arise before the execution of actions, we cannot confidently conclude that the former is causing the latter; there might be a mere temporal correlation between the two events. Nonetheless, this argument alone is insufficient to establish that the conscious will is illusory, as it does not show that motor intentions are in fact *not* causing the actions. One strong demonstration for the case of illusory conscious control would be that our perceived temporal order of intentions and actions are, in fact, false. If intentions, in fact, arise after actions, they could not, in principle, be causing the actions.

Using a cross-modal timing method, Libet (1985) and Libet, Gleason, Wright, and Pearl (1983) have reported that participants start to experience their motor intention at about 200 msec before making a spontaneous finger movement. However, critics have suggested that the reported timings given by participants in the Libet clock paradigm might not be accurate (Joordens, van Duijn, & Spalek, 2002; Klein, 2002; Trevena & Miller, 2002; Gomes, 1998; Dennett & Kinsbourne, 1995; Dennett, 1991; Libet, 1985). In the context of the debate of whether conscious intentions cause actions, a critical possibility is that the reported onset of intentions is determined by neural activity that takes place after action execution. This has not been tested before.

Despite its counterintuitiveness, this possibility is supported by psychophysical research on conscious awareness. Phenomena, such as backward masking (Breitmeyer 1984) and postdiction (Alais & Burr, 2003; Eagleman & Sejnowski, 2000), highlight the retrospective nature of perceptual experience, that is, the intensity and content of an experience can depend on information that only becomes available after the subjective time of perception. In particular, it has been shown that the temporal extent of this retrospective effect can last for as long as 200 msec, as demonstrated in the auditory modality (Alais & Burr, 2003).

We have therefore tested whether transcranial magnetic stimulation (TMS), applied after action execution, has any effect on the reported onset of intention as reported by the participants using the method of Libet et al. (1983). Due to concerns about the absolute accuracy of the reported timings, however, we only assessed the shifts in the reported timings due to TMS, but not the reported absolute measures. Also, because TMS was only applied in half of the trials in a random fashion together with sham TMS, participants could not predict if they were going to be stimulated in a particular trial until the action was executed.

We have previously performed a functional magnetic resonance imaging (fMRI) experiment using Libet et al.'s paradigm (Lau, Rogers, Haggard, & Passingham, 2004), and we found that when participants were required to estimate the onset of their intentions, activations were found in areas that are known to be involved in motor preparation and attention to action, which suggests that, in this paradigm, the participants were in fact trying to

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access information related to the generation of action. In addition to activations in the dorsal prefrontal and parietal cortices that are commonly found in attentionally demanding tasks, we found activation in the pre-supplementary motor area (pre-SMA), which we argued is likely to reflect the representation of intention. The idea that the pre-SMA is particularly important for spontaneous intention is also supported by previous studies. First, it has been reported that electrical stimulation of the medial frontal cortex elicits the feeling of an urge to move (Fried et al., 1991). Second, lesions of the medial frontal cortex abolish self-initiated movements in macaque monkeys (Thaler, Chen, Nixon, Stern, & Passingham, 1995). Finally, we have previously reported activity in the pre-SMA when participants generate actions of their own free choice (Lau, Rogers, & Passingham, 2006). The pre-SMA was therefore chosen as the main site of interest in this study (Figure 2). All stimulations conducted in Experiments 1, 2, and 3 were targeted at this anatomical region. In Experiment 1, we found that TMS after action execution induces shifts in the perceived onset of both intentions and movements. Experiments 2, 3, and 4 were set up to rule out alternative interpretations.

EXPERIMENT 1: MAIN EXPERIMENT

Methods

Six male and four female healthy participants were tested in this experiment. The task instructions were explained to them verbally before they received safety screening and gave informed consent.

The psychological tasks were based on Libet et al.'s (1983) clock paradigm (Figure 1), and the detailed procedures were similar to those used in a previous experiment (Lau, Rogers, Haggard, et al., 2004). Participants rested their head on a chin rest, and in every trial, they watched a red dot revolving around a clock face (diameter ≈ 3°) on a computer screen placed at about 50 cm away from the chin rest. There was a fixation cross presented in the center of the clock face, and participants were required to maintain fixation while the red dot was moving. The dot revolved at a speed of 2560 msec per cycle, and after the first revolution in each trial, the participants were required to press a computer mouse button using their left index finger, at a random time point of their own choice. After the button press, the dot kept on moving for a period of 1280–2560 msec. There was then a delay of 2000 msec, after which the red dot reappeared at the center of the clock face, and participants were required to control the dot as a cursor using another computer mouse held in their right hand.

In the intention condition, they were required to move the cursor to where the dot was when they first felt their intention to press the button. In the movement condition, they were required to move the cursor to where the dot was when they actually pressed the button with their left index finger. After they selected the location, they clicked the mouse button with their right hand to finish the trial. The next trial began after an interval of 1000 msec. In half of the trials, TMS was applied over the pre-SMA. In the remaining trials, there was a sham TMS triggered by another TMS machine with a coil placed near the back of the head of the participants, but directed away from the cortex. The stimulation (real or sham) was either presented immediately after action execution or 200 msec afterwards. There were a total of 240 trials. The two main task conditions were organized into eight 30-trial blocks. Real and sham TMS were randomly allocated, and so were early and late

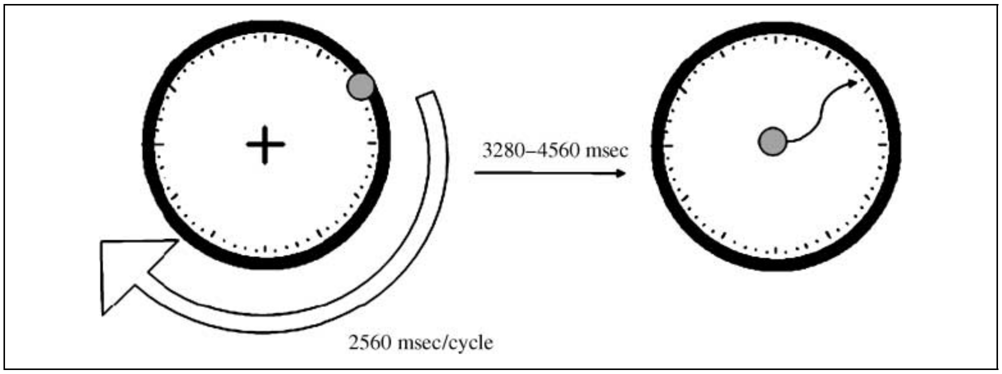

Figure 1. Libet's clock paradigm. Participants made a spontaneous finger movement while watching a red dot revolving around a clock face (left). After the action, the dot kept on going for ½–1 cycle before it disappeared. Then there was a delay, after which the dot reappeared at the center of the clock. Participants used a computer mouse to control the dot as a cursor and moved it to the location where the dot was when they first felt the intention to move in the intention condition, and to the location where the dot was when they actually made the movement in the movement condition.

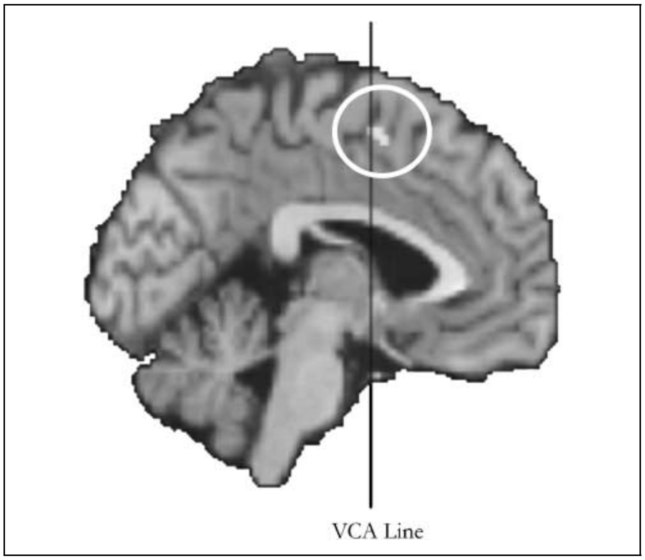

Figure 2. The pre-SMA. This area was the target of stimulation in Experiments 1 to 3. The coordinates (x, y, z = 2, 4, 54) were obtained from a previous fMRI study (Lau, Rogers, Haggard, et al., 2004), and the figure is also adapted from the report of that study. The VCA line vertically passes through the anterior commissure, and is the border between the pre-SMA and the SMA proper.

stimulations. Therefore, from the point of view of the participants, they did not know whether they would be stimulated, or at which point would the pulse be triggered, until after they have pressed the button.

The anatomical site of stimulation was the pre-SMA (Figure 2). The localization for stimulation here was based on the coordinates obtained from the imaging study described in the previous section ($x, y, z,$ = 2, 4, 54). The relationship between the brain of each individual and the standard Talairach space was computed by applying spatial normalization (FLIRT version 5.0, www.fmrib.ox.ac.uk/fsl/flirt/index.html) to the previously acquired MRI scans of each participant, using the Montreal Neurological Institute canonical single-subject, high-resolution MRI image as the template as in the previous fMRI study. Using the Brainsight Frameless System (version 1.5B3, www.rogue-research.com/), the location of the pre-SMA was then marked on each individual's MRI scan, which was then registered with the actual brain in 3-D space. Because the location of the intended site of stimulation is quite far away from the surface of the scalp, a double cone coil (Magstim Company, Whitland, South West Wales, UK) was used in this experiment. The hotspot of the coil was placed directly above the marked position for stimulation on the MRI scan as presented on a computer screen by the Brainsight software. The stimulation pulses were triggered by a Magstim Rapid Rate TMS machine (Magstim Company), and the intensity of stimulation was set at 5% above the active motor threshold for a noticeable foot twitch, tested over the foot area of the motor cortex near the midline. The sham TMS pulses were triggered by a similar TMS machine, and the intensity was adjusted individually for each participant to a level that produced an auditory "click" sound of a volume that was reported to be similar to that of the real TMS.

Experiments 2, 3, and 4 were set up, after obtaining the results in this experiment, to exclude alternative interpretations. Therefore, the procedures were similar to those used in this experiment.

Results

When only sham TMS trials were considered, the group mean for the judged onset of intention was −148 msec (*SD* = 103 msec) relative to the time of the recorded button press. The group mean for the judgment of movement was −50 msec (*SD* = 42 msec). As reported in previous studies (Lau, Rogers, Haggard, et al., 2004; Sirigu et al., 2004; Haggard & Eimer, 1999), the two measures differed significantly [one-tailed t test was used because the test was motivated by evidence observed in previous studies, $t(9) = 2.899, p = .009$].

The effect of TMS for each individual was assessed by subtracting the median judgment value for the sham TMS trials from that of the TMS trials. The group mean for the TMS effect was −9 msec (*SD* = 32 msec) for the intention condition with 0 msec delayed TMS, −16 msec (*SD* = 32 msec) for the intention condition with 200 msec delayed TMS, 14 msec (*SD* = 27 msec) for the movement condition with 0 msec delayed TMS, and 9 msec (*SD* = 16 msec) for the movement condition. These data are plotted in Figure 3. They were entered into an analysis of variance (ANOVA) with task (Intention vs. Movement) and time (0 msec or 200 msec) considered as experimental factors, and it was found that task was a significant factor [$F(1,9) = 24.089, p = .001$] but time was not [$F(1,9) = 0.485, p = .504$). There was no significant interaction between time and task [$F(1,9) = 0.009, p = .926$].

When the data for the different time points of TMS were considered together, it could be shown that the effect of TMS on the judgment of intention is significantly negative to zero[two-tailed t test, $t(9) = -2.6, p = .029$] and the effect on the judgment of movement is, although weaker, significantly positive to zero [two-tailed t test, $t(9) = 2.35, p = .045$].

EXPERIMENT 2: TIME SPECIFICITY

Methods

Seven male and three female healthy participants were tested in this experiment where the effects of TMS applied at other time points were evaluated. The methodology and procedures were similar to those used in Experiment 1, except that the time points for TMS were different. Instead of applying a delay of either 0 msec

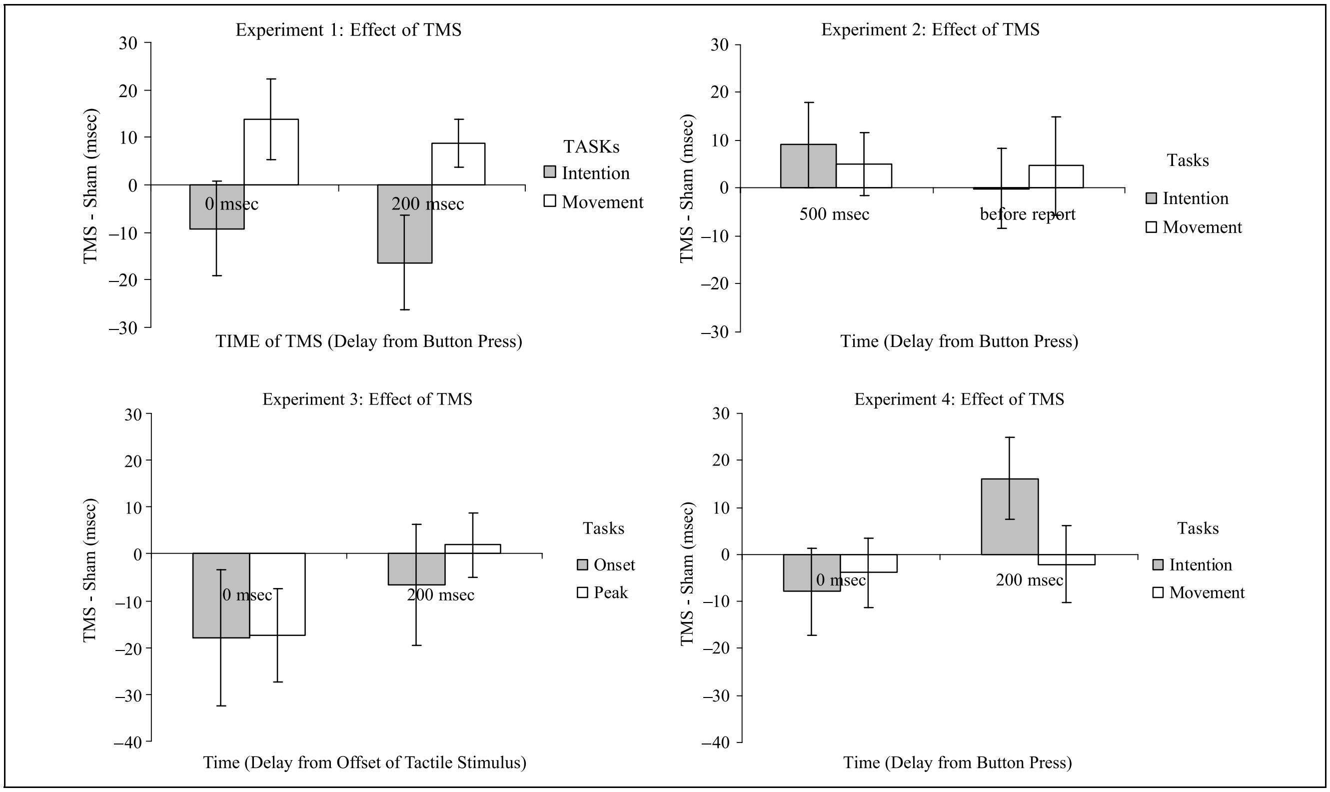

Figure 3. The effects of TMS on the perceived times. TMS produced a forward shift in the reported onset of intention and a backward shift in the reported onset of movement, regardless of whether TMS was administered immediately after the action (button press) or 200 msec afterwards (Experiment 1, top left). This effect of exaggerating the difference between the two reported onsets was significant ($p < .001$, main effect of task in the ANOVA; see also Figure 4). Experiments 2, 3, and 4 were control studies set up to rule out alternative explanations. In Experiment 2 (top right), TMS was administered either 500 msec after the action or immediately before the subjects were required to report the experienced onsets. In Experiment 3 (bottom left), the subjects were required to judge the onset and offset of a slowly ramping-up tactile stimuli (see Figure 5), instead of the onsets of intention and movements; they were not required to make a spontaneous action. Experiment 4 was identical to Experiment 1, except that the motor cortex, instead of the pre-SMA, was targeted in TMS. None of the control studies showed any significant result in the statistical analyses, and the patterns of the effects were clearly different from those observed in Experiment 1. The error bars represent standard errors across participants.

or 200 msec, the delay in this experiment was either 500 msec, or between 3280 and 4560 msec, so that the TMS pulse (shame or real) was triggered at the point when the cursor appeared at the middle of the clock face, prompting the participants to report the estimated timings. These times were chosen to test whether the effect obtained in Experiment 1 was actually due to memory or responding, rather than the experienced onset itself.

Results

When only the sham TMS trials were considered, on average, the participants judged the onset of intention to be −110 msec (*SD* = 82 msec) relative to the times for recorded button press. The average for the judgment of movement was −7 msec (*SD* = 69 msec). The two measures differed significantly [one-tailed t test was used as in Experiment 1 because the test was motivated by evidence observed in previous studies, $t(9) = 4.964$, $p = .0005$].

The group mean for the TMS effect was 9 msec (*SD* = 28 msec) for the intention condition with 500 msec delayed TMS, 0 msec (*SD* = 26 msec) for the intention condition with 3280–4560 msec delayed TMS, 5 msec (*SD* = 21 msec) for the movement condition with 500 msec delayed TMS, and 5 msec (*SD* = 32 msec) for the movement condition with 3280–4560 msec delayed TMS. These data are plotted in Figure 3.

As in Experiment 1, the effects of TMS for each task condition were entered into an ANOVA with task (Intention vs. Movement) and time (500 msec or 3280–4560 msec) considered as experimental factors, and it was found that neither task nor time was a significant factor [$F(1,9) = 0.001$, $p = .974$ and $F(1,9) = 0.208$, $p = .659$, respectively]. There was also no significant interaction between time and task [$F(1,9) = 0.549$, $p = .478$]. The main effect of task was of special interest as this was found to be significant in Experiment 1. However, from the p value it is clear that this effect would not have been significant even if a one-tailed t test had been applied. The size of this effect (i.e., the effect of TMS for intention minus the effect of TMS for movement) is plotted in Figure 4 to allow a comparison across all experiments reported here. Also, the effect of

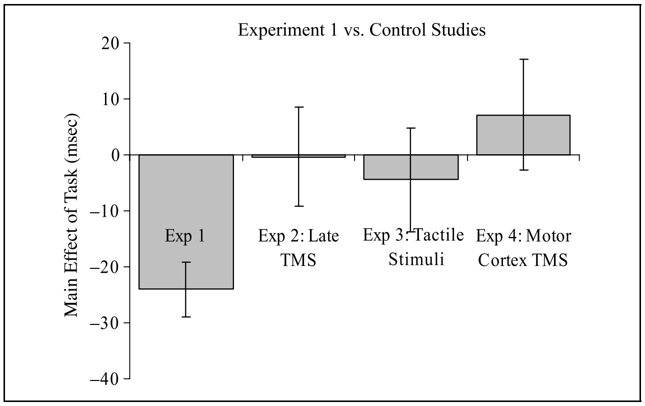

Figure 4. The exaggeration of the difference between the two reported onsets as induced by TMS. Plotted on the vertical scale is the size of the main effect of task, that is, the difference between the effects of TMS on the reported onset of intention and the reported onset of movement (for Experiments 1, 2, and 4) or between the effects of TMS on the reported onset of the tactile stimulus and the reported offset of the stimulus (for Experiment 3). This effect was clearly not present for the control experiments, Experiments 2, 3, and 4 ($p = .974$, .649, and .493, respectively). The error bars represent standard errors across participants.

TMS (TMS vs. sham) was not significant on either the intention task [two-tailed t test, $t(9) = 0.720$, $p = .435$] or the movement task alone [two-tailed t test, $t(9) = 0.818$, $p = .490$].

The effect of task was also assessed when the trials for the different time points of TMS were considered separately. One-tailed t test was used based on the results obtained in Experiment 1 to maximize statistical power. The effect of task was not significant for either the 500 msec trials [direction of effect opposite to prediction based on Experiment 1, one-tailed t test, $t(9) = -0.694$, $p = ns$] or the 3280–4560 msec trials [one-tailed t test, $t(9) = 0.331$, $p = .374$].

EXPERIMENT 3: MODALITY SPECIFICITY

Methods

Eight male and two female healthy participants were tested in this experiment, which was set up to test if the effect in Experiment 1 was actually due to the general mechanism of cross-modal timing using the clock face. In particular, we wanted to know whether TMS simply exaggerates the perceived temporal difference between early and late events. This was tested by presenting a tactile stimulus to the subjects and requiring them to judge the timing of this stimulus using the clock. The methodology and procedures were similar to those used in Experiment 1. Instead of requiring the participants to make a self-paced left index finger movement, a slowly ramping up tactile stimulus (duration = 600 msec) was applied to the tip of this finger at a random time point (2960–7980 msec) in every trial. The tactile stimulus used here had the same property of slowly ramping up that is characteristic of the electrophysiological measures of the readiness potential (Deecke, Scheid, & Kornhuber, 1969; Kornhuber & Deecke, 1965). Instead of estimating the onset of intention and movement, participants were required to estimate the timing of either the onset or the peak of the tactile stimulus using the Libet clock. A small tactile stimulator (100-Ω bone conduction vibrators; Oticon, Hamilton, Scotland) was connected to the audio output from the sound card of a PC, where a wave file containing white noise was played, to give the tactile sensation. The intensity of the stimulation was set at a low level, only slightly beyond detection threshold for each participant, such that the earliest part of the stimulation would not be felt. The tactile stimulator and the left index finger of the participants were inserted into a piece-insulating sponge so as to minimize the auditory noise associated with the tactile stimulus. TMS was triggered at either 0 msec or 200 msec after the offset of the tactile stimulus.

Results

When only the sham TMS trials were considered, on average, the participants judged the onset of the tactile stimulus to be −107 msec (*SD* = 95 msec) relative to the offset of the stimulus. The average for the judgment of the peak of the stimulus was 26 msec (*SD* = 92 msec) relative to the actual offset of the stimulus. The two measures differed significantly [one-tailed t test used as in Experiment 1, $t(9) = 4.764$, $p = .0005$], and the magnitude of this difference was similar to the difference between the intention judgment and movement judgment in Experiment 1 (see Figure 5).

The group mean for the TMS effect was −18 msec (*SD* = 46 msec) for the onset timing condition with 0 msec delayed TMS, −7 msec (*SD* = 41 msec) for the onset timing condition with 200 msec delayed TMS, −17 msec (*SD* = 31 msec) for the peak timing condition with 0 msec delayed TMS, and 2 msec (*SD* = 22 msec) for the peak timing condition with 200 msec delayed TMS. These data are plotted in Figure 3.

As in Experiment 1, the effects of TMS for each task condition were entered into an ANOVA with task (Onset Timing vs. Offset Timing) and time (0 msec or 200 msec) considered as experimental factors, and it was found that neither task nor time was a significant factor [$F(1,9) = 0.222$, $p = .649$ and $F(1,9) = 1.716$, $p = .223$, respectively]. There was also no significant interaction between the two factors [$F(1,9) = 0.159$, $p = .699$]. The main effect of task was of special interest as this was found to be significant in Experiment 1. However, from the p value it is clear that this effect would not have been significant even if a one-tailed t test was applied. The size of this effect (the effect of TMS for onset timing minus the effect of TMS for peak timing) is plotted in Figure 4 to allow a comparison across all experiments reported here.

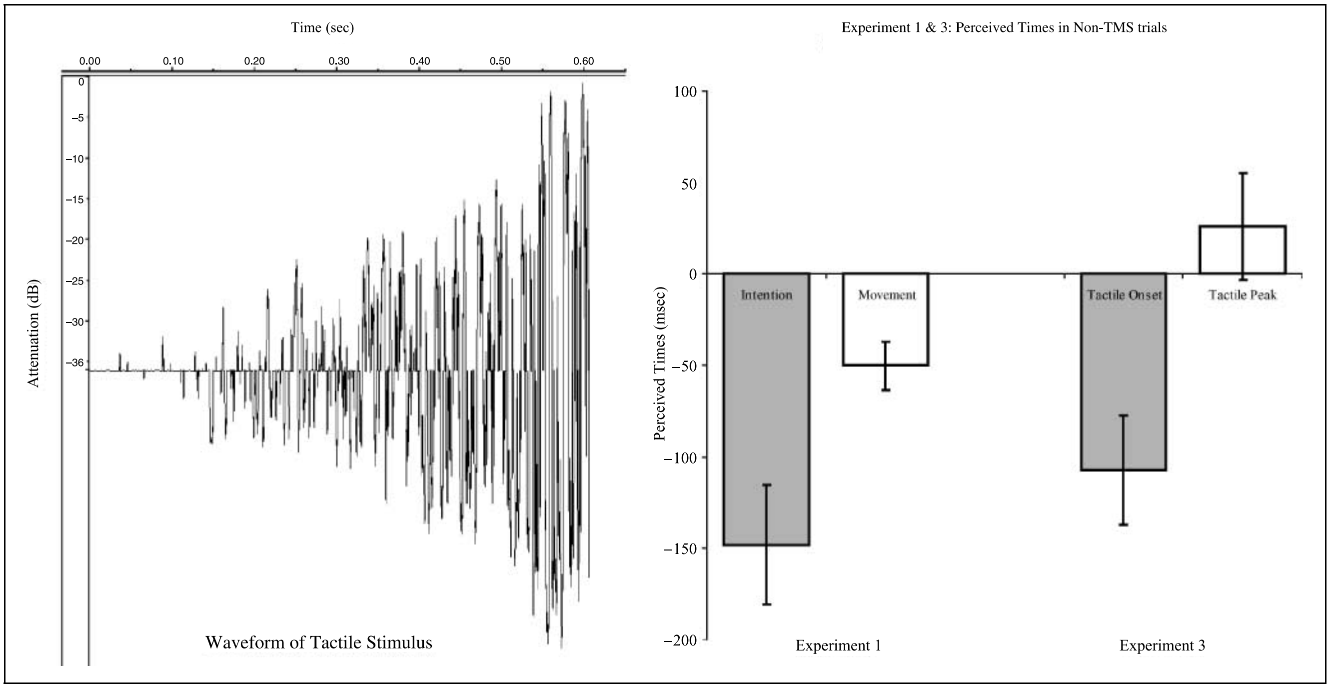

Figure 5. The temporal profile of the tactile stimulus used in Experiment 3. The tactile stimulus used in Experiment 3 took a slowly ramping-up form (left), and was presented at a low intensity such that the early part of the stimulus was not felt. This was set up to mimic the form of the readiness potential preceding spontaneous actions (Deecke et al., 1969; Kornhuber & Deecke, 1965). The magnitude of the difference between the perceived onset of the tactile stimulus and the perceived time of the peak of the stimulus in Experiment 3 was very similar to the magnitude of the difference between the perceived onset of intention and the perceived time of movement in Experiment 1 (right).

Also, the effect of TMS (TMS vs. sham) was not significant on either the onset judgments [two-tailed *t* test, $t(9) = -1.197, p = .262$] or the offset judgments alone [two-tailed *t* test, $t(9) = -1.185, p = .266$].

Despite the fact that task was not found to be a significant factor for the effect of TMS in this experiment, the magnitude of the effect of TMS on the onset judgments was somewhat similar to that of the effect of TMS on intention in Experiment 1. However, this nonsignificant effect was not specific to onset judgment alone but was also there in offset judgments, which means that, unlike in Experiment 1, this effect was not specific to task. It is likely that because TMS produces a tactile sensation to the scalp, it produced a nonspecific interference with the tactile judgments in general. That would fit with the fact that this effect was stronger for the TMS applied closer to the stimuli. In any case, it is clear that TMS did not exaggerate the perceived temporal difference between early and late events as observed in Experiment 1.

EXPERIMENT 4: ANATOMICAL SPECIFICITY

Methods

Seven male and three female healthy participants were tested in this experiment in which we try to assess if the effect obtained in the experiment was simply because TMS added noise to the motor system. The methodology and procedures were similar to those used in Experiment 1, except that the site of TMS was the right primary motor cortex instead of the pre-SMA. Because of the ease of accessibility of the motor cortex as shown in previous studies, a normal figure-of-eight shaped coil (Double 70mm Coil, Magstim, www.magstim.com/Products.html) was used. The localization of the primary motor cortex was done by checking the intensity of TMS-induced motor twitch for the first dorsal interosseus in the right hand of the participants while moving the coil around the expected region of the scalp. Once the most sensitive spot was identified, the threshold for stimulation was set at 5% above the active motor threshold for a noticeable hand twitch.

Results

When only the sham TMS trials were considered, the group mean for the judged onset of intention was −99 msec (*SD* = 79 msec) relative to the time of the recorded button press. The group mean for the judgment of movement was −13 msec (*SD* = 76 msec). The two measures differed significantly [one-tailed *t* test as in Experiment 1 because the test was motivated by evidence observed in previous studies, $t(9) = 3.733, p = .002$].

The group mean for the TMS effect was −8 msec (*SD* = 30 msec) for the intention condition with 0 msec delayed TMS, 16 msec (*SD* = 28 msec) for the intention condition with 200 msec delayed TMS, −4 msec (*SD* =

23 msec) the movement condition with 0 msec delayed TMS, and −2 msec (*SD* = 26 msec) for the movement condition with 200 msec delayed TMS. These data are plotted in Figure 3.

As in Experiment 1, the effects of TMS for each task condition were entered into an ANOVA with task (Intention vs. Movement) and time (0 msec or 200 msec) considered as experimental factors, and it was found that neither task nor time was a significant factor [$F(1,9) = 0.510, p = .493$ and $F(1,9) = 2.418, p = .154$, respectively]. There was also no significant interaction between time and task [$F(1,9) = 2.052, p = .186$]. The main effect of task was of special interest as this was found to be significant in Experiment 1. However, from the *p* value it is clear that this effect would not have been significant even if a one-tailed *t* test was applied. The size of this effect (i.e., the effect of TMS for intention minus the effect of TMS for movement) is plotted in Figure 4 to allow a comparison across all experiments reported here.

Also, the effect of TMS (TMS vs. sham) was not significant on either the intention task [two-tailed *t* test, $t(9) = 0.686, p = .510$] or the movement task alone [two-tailed *t* test, $t(9) = -0.456, p = .659$].

DISCUSSION

Summary of Findings

To summarize the results, Experiment 1 showed that there was a retrospective effect for TMS over the pre-SMA on the perceived onset of intention as well as for perceived timing of the movement itself. TMS shifted the perceived onset of intention backward in time and shifted the perceived timing of the movement forward in time. The main effect of task, that is, the differential effect on intention and movement, is about 24 msec. This difference is not driven by the TMS effect on the movement condition alone, as the effect of TMS in the intention condition is also significant on its own. This differential effect was found for both stimulations applied at 0 msec and 200 msec after action execution.

One could argue that the TMS effect we have observed was not genuinely retrospective, but rather, it simply affected the memory of timing, or the reporting of the timing, which took place after the TMS. However, Experiment 2 showed that the effect observed in Experiment 1, that is, the exaggeration of the difference of the judgments for the onsets of intention and movement, was not found when TMS was applied at 500 msec after the action or right before the participants made their reports of their time estimates. One could argue that this only shows that there is a critical time window within which memory is susceptible to manipulation. However, this interpretation would require the ad hoc assumption that an experience could be first generated and *then* misremembered as something else, unbeknownst to the subject. If this assumption is allowed, one could as well argue against the existence of well-established phenomena, such as backward masking (Breitmeyer, 1984) and flash-lag (Nijhawan, 1994, 2002; Eagleman & Sejnowski, 2000), by reinterpreting them as results of failure or change of memory. Although philosophers have pointed out that we cannot unequivocally reject these alternative interpretations (Dennett & Kinsbourne, 1995; Dennett, 1991), one generally prefers parsimonious explanations that do not require ad hoc assumptions.

Neither did we observe the same effect when we tested this for the tactile modality, as shown in Experiment 3 when the same timing method was used. This suggests that TMS did not simply affect the visual processing required to make accurate judgments in the Libet task. In particular, TMS did not simply exaggerate the perceived temporal difference between early and late events. The tactile task in Experiment 3 was similar in structure to the task in Experiment 1. When only the control sham TMS trials where considered, the differences between the perceived onset of the tactile stimulus and the perceived time for its peak were very similar to the differences between the perceived onset of intention and perceived time of movement (see Figure 4). Yet, no significant effect was observed in Experiment 3.

The targeted anatomical site of stimulation of Experiments 1 to 3 was the pre-SMA. This anatomical localization was based on the fMRI results of our previous study (Lau, Rogers, Haggard, et al., 2004), and each individual participant's structural MRI scan. However, we could not be sure that only the pre-SMA was stimulated, as it was not clear if TMS afforded such high spatial specificity, especially given the potential spread of the effect and interaction between different areas. Also, the lateral premotor areas might have been stimulated by the magnetic fields generated by the wings of the double-cone coil used in this experiment, too. Nonetheless, the conclusion of the study does not depend on the precision of the stimulation, as the main question is about whether the experience of intention is fully determined before action execution, but not about where it is represented in the brain. Experiment 4 further showed that the effect observed in Experiment 1 is, in fact, reasonably specific, in that even when another area in the motor system (the primary motor cortex) is stimulated, the same effect is not observed. This suggests that the effect was not simply due to the fact that TMS added noise to the motor system or that participants were simply startled.

Effect Size and Reliability of the Data

One could argue that the temporal shifts produced by TMS are small, and thus, unimpressive. Due to considerations about the safety and comfort of the participants, we did not apply the stimulations at a higher intensity or in a rapid-rate, repetitive fashion. This might be one reason why the size of the effect did not appear to be very large. However, the size of the temporal shifts cannot be directly compared with the results obtained in most other cognitive TMS experiments (Walsh & Pascual-Leone, 2003; Stewart, Ellison, Walsh, & Cowey, 2001), as the common measures in previous experiments are normally a change in reaction times or error rates, which are very different from subjective onset estimates. One study (Haggard, Clark, & Kalogeras, 2002), which used the same paradigm to investigate the retrospective effect of external stimuli on the perceived onset of movement (but not intention), revealed a temporal shift of only 15 msec. Another study (Haggard & Magno, 1999) used the same paradigm to investigate the prospective effect of TMS on the perceived onset of movement (but not intention), and one of the targeted areas of stimulation was close to the pre-SMA (FCz). It was found that TMS applied to this area prior to action execution can only shift the perceived onset of movement by 54 msec, even when the actual shift of movement execution was as large as 113 msec. Taken together, it seems that experimentally induced temporal shifts as measured by the Libet method are, in general, not very large. Nonetheless, this does not mean that the measures are uninformative, as the principled way to assess the significance of an effect and compare it with other studies that use different measures is to characterize it in terms of the variance of the data (i.e., to look at the statistical effect size). The eta-squared value, which is a standard estimate of statistical effect size, is .728 for the main effect of task in Experiment 1; the corresponding p value is as small as .001. This is a relatively high level of significance as far as cognitive TMS experiments are concerned.

Despite this high level of statistical significance, and the fact that each experiment involved 10 subjects (even for each control studies), there might still be concerns about the reliability of the presented data. In particular, the baseline values of the reported onsets (i.e., values for sham TMS trials) fluctuated across Experiment 1 and the control studies. This could be due to the fact that some of the control studies differed from Experiment 1 in various aspects: Experiment 2 presented sham TMS at later time points; Experiment 3 required subjects to judge the timing of a tactile stimulus instead of a self-generated action; Experiment 4 presented the sham TMS using a different coil in order to match for the sound of the TMS administered in that experiment. These suggest that subtle factors, such as the auditory level and the timing of the sham TMS, could, in fact, affect the reported onsets in this difficult timing task.

Also, the variability of the effect of TMS was also a source of concern. Although the statistical analyses revealed no significant effect in all control studies, there were sometimes weak trends observed in unpredicted directions, as shown in Figure 3. We emphasize that TMS exaggerated the difference between the reported onsets of intention and movement in a robust fashion, and this effect was clearly not present in the control studies, as shown in Figure 4. This is the main effect of interest in the article. Nonetheless, one major limitation could be that the control studies involved different experimental sessions and did not always involve the same subjects. Future studies would benefit from replicating these results in the same sessions by, for instance, testing more different time points of TMS in each session, thereby combining and replicating the results of Experiments 1 and 2, and possibly exploring other critical time points such as those before action execution as well.

Direction of Temporal Shifts

In Experiment 1, it was found that retrospective TMS shifted the perceived onset of intention backward in time, and shifted the perceived timing of action execution forward in time. The directions of these effects were not predicted a priori. Here we offer a tentative model to account for this pattern of temporal shifts, which we hope could be tested in future experiments.

When performing difficult perceptual tasks, we often try to combine information from different sources, such as cues from different sensory modalities. A natural and optimal method to combine these different sources of information is to perform Bayesian cue integration (Knill & Pouget, 2004). Assuming that the noise or uncertainty in the information can be characterized as Gaussian in form, this method amounts to taking a weighted average of the information from the different sources, where the weights are inversely proportional to the amount of noise in each respective source.

The readiness potential (Deecke et al., 1969; Kornhuber & Deecke, 1965), measurable by EEG from the scalp, reflects the slowly ramping-up neural activity that precedes spontaneous movements. It has been argued that the readiness potential comprises different components that are functionally distinct (Deecke, 1987). The earliest onset of the readiness potential is around 1 to 1.5 sec. Despite the lack of an uncontroversial method to measure accurately the onset of the experience of intention, it seems plausible that the experienced onset is not as early as the onset of the readiness potential. One possibility is that due to the difficult nature of the task to estimate the onset of intention, the brain combines the information reflected by both the early and the late components of the readiness potential. The late components of the readiness potential might indicate that the onset of intention is much closer to the time of action execution, and because the signal of the early component of the readiness potential is weak, the weighting for the representation reflected by early component is likely to be low. That might explain why we typically experience the onset of the intention as much later than the onset of the readiness potential.

It has been suggested that the best way to characterize the effect of TMS is to view it as adding neural noise to the targeted cortical area (Walsh & Pascual-Leone, 2003). The pre-SMA is likely to be one of the sources of the readiness potential (Cunnington, Windischberger, Deecke, & Moser, 2002). Because TMS is applied after action execution in the experiments described in this article, it is reasonable to assume that noise is mostly added to the late components of the readiness potential, but not the early ones. If the brain combines the timing information of intention in a way that is similar to optimal Bayesian cue integration, increasing the uncertainty of the representations reflected by the late components of the readiness potential would decrease the weight assign to these representations, and thus, increase the relative weight for the early components. The result would be that we estimate the onset of intention to be earlier.

Similarly, when estimating the timing of action execution, the brain might combine the information from proprioceptive sensory feedback as well as from the representations reflected by the late components of the readiness potential. The late components of the readiness potential may indicate an earlier time of action execution than does the sensory feedback, as the former is a preparatory signal. According to the model, adding noise to the late component would lead to a forward temporal shift of the resulted estimation, as the relative weight for the sensory feedback is increased.

To explain the present data, the model need not be fully Bayesian in nature, in the sense that it explicitly represents the probability distribution functions for the different cues. Neither does it require the assumption that noise has a Gaussian structure or is normally distributed. The foregoing explanation could be derived so long as the system weighs the different cues according to the noise associated with each cue, so that the higher the noise, the smaller the weight would be ascribed to that cue.

Conclusions

The main conclusion of this article does not depend on the aforementioned model. Regardless of what mechanism is used in the brain, the results suggest that the perceived onset of intention depends on neural activity that can be manipulated by TMS at as late as 200 msec after the execution of a spontaneous action. The mechanism for this retrospective effect is unclear. One possibility is that TMS over the medial frontal area interferes with feedback processes that confirm the execution of the action. The present data also do not determine whether neural activity that takes place before the execution of the action is sufficient to yield some form of experience of intention. It could be the case that some weaker form of experience of intention is sufficiently determined by neural activity that takes place before the execution of the action, and such experience might have some causal impact on the control of the action. One way to examine this possibility would be to apply TMS before the execution of action, as suggested above, and compare the effect with those obtained in this study. Although the onsets of spontaneous actions cannot be easily predicted, TMS could be delivered at random time points. Given sufficient number of trials, one could identify, after the experiment, the trials where TMS are delivered just before action onsets, and perform the analysis on these trials. Before this experiment is conducted, however, one cannot draw the strong conclusion that the experience of having conscious control of a simple motor action is entirely illusory.

Nonetheless, the current results throw doubt on the commonsensical view that the experience of intention, including the experienced onset, is completely determined before an action. The commonsensical view is attractive when we assume that the main function of experience of intention is for the conscious control of action, but it cannot account for the data presented here. The data suggest that the perceived onset of intention depends at least in part on neural activity that takes place after the execution of action, which could not, in principle, have any causal impact on the action itself. An alternative view that is compatible with the data is that one function of the experience of intention might be to help clarify the ownership of actions (Wegner, 2002, 2003), which can help to guide future actions. This process could take place immediately after action execution.

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