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Intentional action: Conscious experience and neural prediction

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Abstract

Intentional action involves both a series of neural events in the motor areas of the brain, and also a distinctive conscious experience that “I” am the author of the action. This paper investigates some possible ways in which these neural and phenomenal events may be related. Recent models of motor prediction are relevant to the conscious experience of action as well as to its neural control. Such models depend critically on matching the actual consequences of a movement against its internally predicted effects. However, it remains unclear whether our conscious experience of action depends on a precise matching process, or a retrospective inference that “I” must have been responsible for a particular event. We report an experiment in which normal subjects judged the perceived time of either intentional actions, involuntary movements, or subsequent effects (auditory tones) of these. We found that the subject’s intention to produce the auditory tone produced an intentional binding between the perceived times of the subject’s action and the tone. However, if the intention was interrupted by an imposed involuntary movement, followed by the identical tone, no such binding occurred. The phenomenology of intentional action requires an appropriate predictive link between intentions and effects, rather than a retrospective inference that “I” caused the effect. © 2003 Elsevier Inc. All rights reserved.

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1. Introduction

Intentional, self-initiated action involves a characteristic set of brain processes, which are quite distinct from the brain processes involved in reflex or responsive movements. For example, functional imaging studies of intentional actions typically show activation in the basal ganglia and

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supplementary motor area (SMA), while studies of externally triggered actions show activation in the cerebellum and premotor cortex (Cunnington et al., 1996; Jahanshahi et al., 1995; Passingham, 1987). These two routes to action converge only at the primary motor cortex, a single synapse away from the muscles themselves.

In addition to these neural differences, there are clear differences between the conscious experiences of intentional action and of unintentional body movements. To understand these differences, we consider three levels of conscious experience of action: body movement, source of action, and authorship. The lowest level refers to the somatosensory experience of movement of part of the body. Any action produces characteristic somatosensory and proprioceptive experiences localised to the moved body part. Proprioceptive sensation, even at this lowest level, differentiates between active and passive body movements (Paillard & Brouchon, 1968), and conscious sensations associated with intended and passive movements of the body are quite different (Blakemore, Wolpert, & Frith, 1998). The next level refers to our experience of *why* we act, and involves the concept of sources of action. We normally experience our actions as flowing from a source, or reason for action. Conscious intention is the experience of the source of our actions (Marcel, in press). Finally, a third level involves associating intentions with persons, and involves the sense of authorship (Gallagher, 2000), namely that “I” caused this action, rather than another agent.

This paper focuses on the middle level of representation, and the experience of intentions as the source of action. The contribution of intention to action awareness can be expressed by introducing two teleological concepts. The first is the concept of an action *goal*, or state of affairs in the external world that the action aims to produce. Intentional actions are typically made for the purpose of achieving a specific goal. Cognitive representations seem concerned with goals, and only secondarily with the movements used to achieve them (Bekkering & Wohlschläger, 2002). The second, more complex concept relates to the causal chain between intention and action. The normal experience of intentional action includes an implicit content that the action occurred *because*, and *via* the intention that the agent had to perform it. As Marcel (2003) has pointed out, a powerful example of the source of an action occurs in cases of anarchic hand syndrome and utilisation behaviour (Boccardi, Della Sala, Motto, & Spinnler, 2002). These patients, who typically show bilateral frontal mesial damage to the supplementary motor area (SMA), or unilateral SMA and callosal damage (Della Sala, Marchetti, & Spinnler, 1991) magnetically respond to environmental objects without a specific intention to do so. For example, the mere presence of a pen on a table will lead them to pick it up and start writing “because it’s there,” even if they have no particular intention to write anything. The patient does not deny authorship of the action, but they clearly have no conscious experience that their intentions are the *source* of the action: “my hands move by themselves” (p. 293).

In normal life, the operations of all three levels provide a coherent experience that we control our actions. In special cases, however, the levels can be dissociated. For example, in experiments on action attribution, subjects can accept as their own an action which is made by another person. In these cases, there is a sense of authorship in the absence of appropriate information about the source and somatosensory consequences of action. Anarchic hand patients acknowledge that movements of the anarchic hand are made by them, but insist they are not intended (Marcel, 2003). In this case there is a sense of authorship, but no conscious awareness of the source of the affected hand’s action. Any mismatch between body movements, conscious intention, and

authorship undermines the sense of agency, and often feels personally threatening. Both split-brain patients (Gazzaniga, 1995) and indeed normal subjects (Wegner & Wheatley, 1999) may retrospectively attribute intentions to themselves to explain their actions.

The concept of action sources also reveals a clear temporal structure in the awareness of action. It is often experimentally convenient to treat an action as a discrete temporal event, as in reaction time studies. In fact, however, intentional actions involve an extended stream of neural events, occurring in a distinct order. Sources of action must precede actions, and actions must precede their goals or effects. The neural preparation of a motor act necessarily precedes actual movement of the body. Similarly, movement of the body towards a goal necessarily precedes actually achieving the goal itself. In addition, sensory awareness that the goal has truly been reached is necessarily delayed by transmission from the sensory receptors to the brain. Several studies have investigated the time at which subjects perceive their own actions to occur (Libet, Gleason, & Wright, 1983; McCloskey, Colebatch, Potter, & Burke, 1983). Such studies effectively locate the perceptual centre (Morton, Marcus, & Frankish, 1976) of this extended stream of neural events. The general finding has been that the intention to act makes a substantial contribution to awareness of the action itself (Haggard, in press; Haggard, Newman, & Magno, 1999). In addition, there is a strong and reciprocal attraction between the awareness of actions and the awareness of the effects of an action. Specifically, intentional actions are perceived as shifted forward in time towards the effects that they produce, while the effects of intentional actions are perceived as shifted backwards in time towards the actions that produced them (Haggard, Aschersleben, Gehrke, & Prinz, 2002). This effect, which we called *intentional binding* depends critically on the intention to produce the effect: when similar movements and auditory effects occurred involuntarily rather than by the subject's intention, the binding effect was reversed (Haggard, Clark, & Kalogeras, 2002; Tsakiris & Haggard, 2003).

While the effects of intentional binding are clear, the neural mechanisms that give rise to it are not clear. There are at least two possible explanations. First, intentional binding is consistent with the broad class of predictive models of movement control (Wolpert, 1997). In such models, an efference copy of the motor command is processed by a dedicated neural circuit, so as to predict the consequences of action before sensory information about them becomes available. Three specific features of intentional binding are consistent with this model. First, intentional binding requires an efferent signal, similar to the motor command posited by predictive models. Second, intentional binding requires reliable temporal relations between action and effect (Haggard et al., 2002). In the same way, predictive models learn the relation between motor command and sensory consequence. Third, intentional binding causes *anticipatory* awareness of action effects: this shift is a direction which suggests prediction.

On the predictive account, the conscious experience of action would be constructed at the time of the action itself, as an immediate by-product of the motor control circuits that generate and control the physical movement itself. Crucially, the conscious experience can be directly related to the underlying neural motor processes that cause the action: the experience is tied to the *source* of the action. This recalls Searle's (1983) concept of causal self-referentiality. The predictive modal account fits with what we will call a constructive view of conscious intention.

The second candidate explanation of intentional binding involves a reconstructive view of conscious intention. On this view, we retrospectively infer conscious experiences of our own

intentional actions to explain what happens. Thus, if I first feel my finger moving, and then hear an auditory tone, I will infer a conscious intention to move, and reconstruct the intention as being the cause of both movement and the tone. The source of action is not experienced directly, but is invented post hoc. This model has a strongly Humean flavour, because it retrospectively infers the presence of an apparent cause, conscious intention, based on repeated experience of its effects. Humean models have received some support from studies on attribution of intention in situations of ambiguous authorship. Thus, subjects (Wegner & Wheatley, 1999) may retrospectively attribute to themselves conscious intentions to explain actions that were in fact performed by another person, but could have been performed by them. It remains unclear whether Humean models can explain the basic process of binding intentions actions and effects in the absence of ambiguity of authorship.

Here, we report an experiment which attempts to distinguish Searlean and Humean models of intentional binding. Specifically, we asked subjects to produce intentional actions, which were followed by a beep. In some blocks, we randomly interrupted the subject's intention by applying involuntary movements, which were physically similar to the intentional actions, using TMS. Both intentional actions and involuntary movements were followed 250 ms later by an auditory tone. Thus, the conjunction of finger movement and tone was always present. However, in some trials the subject caused the tone by a normal process which precisely matched the subject's intention, while in other trials the same conjunction of events occurred, but not precisely matching the subject's intention. Subjects judged the perceived time of either their voluntary action, or the involuntary movement, as appropriate. In other blocks, they judged the perceived time of the auditory tone. We observed intentional binding only for trials where the tone was produced in a way that directly matched the subject's intention, and not in those trials where comparable events occurred without matching the intention in an appropriate way. The results are consistent with a predictive model that constructs conscious experience of action as part of the process of action execution, but not with a reconstruction of intentional action based on retrospective inference.

2. Method

The experiment was broadly based on experiment 1 of Haggard et al. (2002), and used Libet's method (Libet et al., 1983) to measure the perceived time of events. Therefore, the methods are described only briefly here (see Fig. 1).

Eight naïve healthy right-handed subjects (age 18–26, 6 female) participated with ethical permission. They viewed a clock face with a single hand (length 12 mm) rotating every 2560 ms, and marked with conventional 5 “minute” intervals. After a random delay one of 3 events would occur. The clock rotated for a further random interval, and subjects then judged the position of the clock hand when they perceived the onset of the event. Subjects entered their judgements on a keypad with their left hand. Subjects were encouraged to judge the event onsets with as much precision as possible, and not to restrict themselves to the marked values on the clock face.

In single-event baseline blocks, the events were either an ambient auditory tone (frequency 1 kHz, duration 100 ms), a voluntary keypress made with the right index finger, or an involuntary

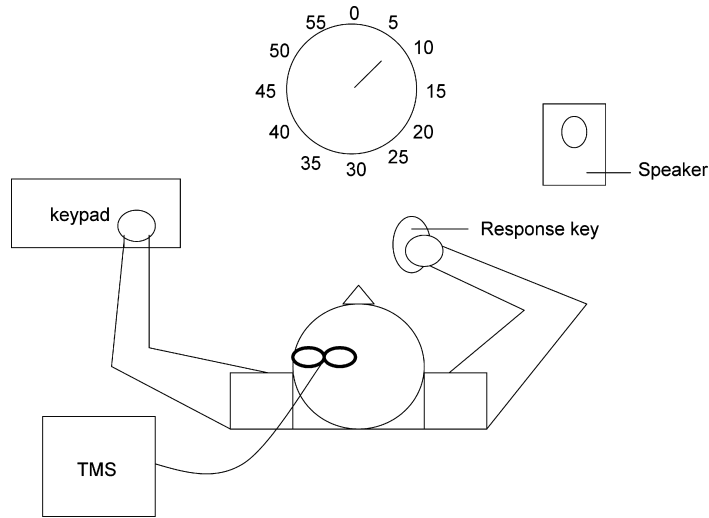


Fig. 1. Schematic of the apparatus.

movement of the right index finger, induced by transcranial magnetic stimulation over the left motor cortex. Subjects were asked to make voluntary actions within the first 1.5 rotations of the clock (0.5–3.84 s after trial onset), to avoid responding to specific clock positions, and to make the action at a time of their own choosing. TMS-induced movements and auditory tones were programmed to occur at comparable random latencies. The restricted time window for voluntary action might reduce the involvement of “free will,” but allows experimental interventions to be interposed into the process of intentional preparation (see below).

The experimental blocks were of two kinds, mixed and unmixed. In the mixed blocks, subjects were instructed to make an intentional action as before. In addition, TMS was programmed to occur at the same latency range. Thus, on any given trial, and depending on the progress of the subject’s intentional action, either the intentional action could occur first, or the involuntary TMS-induced movement could occur first. If the subject “beat” the TMS, then the TMS was cancelled, and the intentional action was followed 250 ms later by an auditory tone. If the TMS “beat” the subject, then the TMS was followed 270 ms later by an identical auditory tone. This 270 ms latency was intended to produce a 250 ms interval between the TMS-induced movement and the tone, since the delay between TMS delivery and finger movement is typically 20 ms in normal healthy subjects. The subject was instructed to abandon any intentional action if their preparation was interrupted by TMS. In half the mixed blocks, subjects judged the time of their keypress, or the time of the similar TMS-induced involuntary movement, whichever occurred on that trial. In the remaining experimental blocks, subjects judged the beep which followed these movements. The experimental blocks were forked after running the experiment, to analyse separately trials where an intentional action occurred, and those where the preparation of action was interrupted by TMS.

Finally, we also included two unmixed blocks, in which TMS was delivered as before, followed 270 ms later by the auditory tone. Subjects never made voluntary actions in these blocks, so intention was presumably absent. In one block subjects judged the involuntary TMS-induced

movement, and in the other subjects judged the tone onset. These blocks served as controls for comparison with judgements of these events in the mixed blocks.

There were three single-event baseline blocks, two repetitions of the mixed block in which subjects judged whichever of the voluntary action or TMS-induced movement occurred on each trial, two repetitions of the mixed block in which subjects judged the tone, and two unmixed blocks. The various events that occurred in each block are shown in Fig. 2. Each subject performed the nine blocks in a different random order, with the constraint that the two repetitions of each mixed block type could not immediately follow each other. Each block consisted of 40 trials.

2.1. Physiological methods

Transcranial magnetic stimulation (TMS) was delivered from a Magstim 200 stimulator using a “figure of eight” coil (Magstim, Whitland, UK) at the optimal location over the left motor cortex

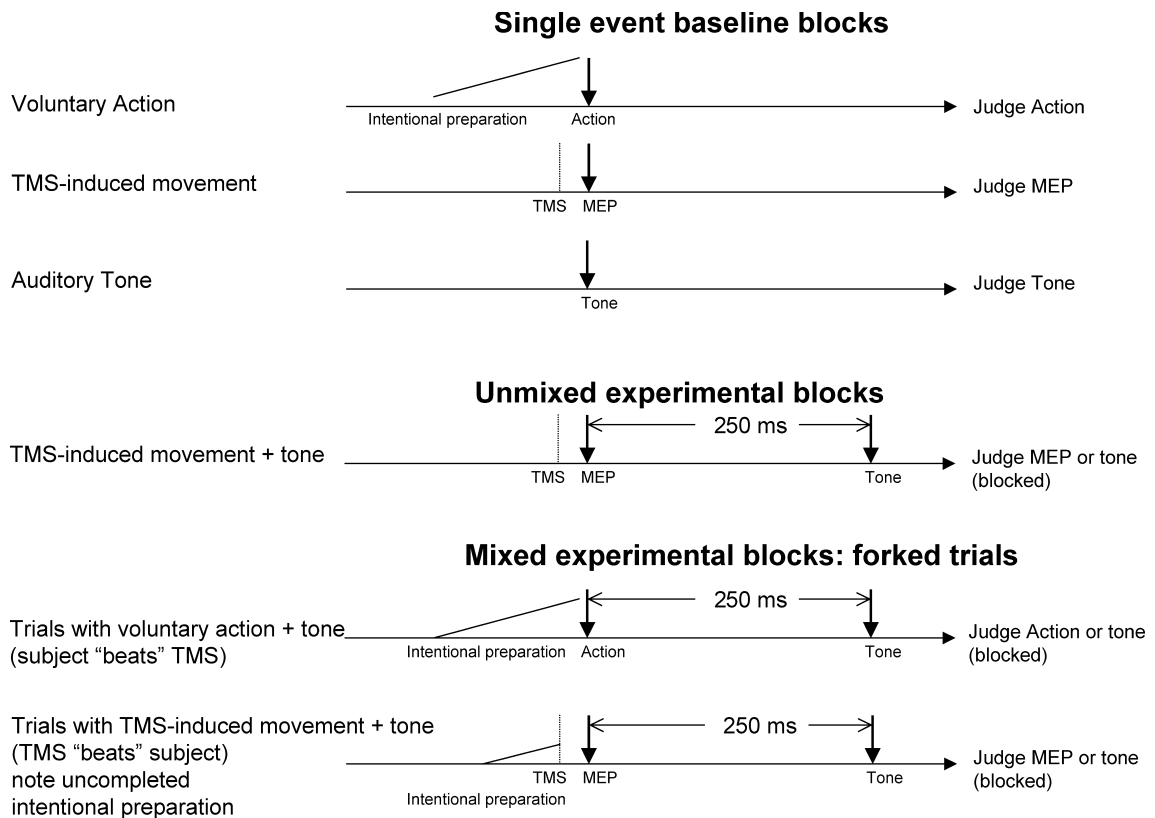


Fig. 2. Schematic of events in each condition. A rising diagonal indicates intentional preparation for voluntary action. In single-event baseline blocks, either actions, involuntary TMS-induced movements (MEPs) or tones occur according to condition, and subjects judge the time of the event. In unmixed blocks, MEPs are followed by tones. Subjects judge the MEP or the tone, in separate blocks. In mixed blocks, subjects prepare and make intentional actions, but may be interrupted on random trials by TMS. Both actions and MEPs are followed by tones. On half the blocks subjects judge the tone. On the other half, they judge whichever of the action or the MEP occurred on that trial.

for producing motor evoked potentials (MEPs) in the right first dorsal interosseus muscle. The stimulator creates a transient magnetic field which passes unattenuated through scalp and tissue, inducing electrical currents in the local area of cortex immediately underneath the centre of the coil. This in turn depolarises cortical neurons, producing a descending volley which is conducted to contralateral muscles and produces a measurable contraction of the target muscle (Motor Evoked Potential—MEP). The motor threshold was calculated by for each subject, by reducing stimulator output in 5% steps to find the lowest level at which three MEPs exceeding 50 μ V peak amplitude were obtained from five successive stimulations of the relaxed 1DI. The first dorsal interosseus muscle was chosen as it flexes the index finger, and is thus involved in voluntary keypresses. During the experiment, the stimulus intensity was set at 120% of each subject's motor threshold. Activity of the first dorsal interosseus muscle was measured with Ag–AgCl electrodes, amplified, and digitised at 5 kHz, rectified and smoothed (cutoff 25 Hz, second order Butterworth filter).

2.2. Analysis

A judgement error was calculated for each trial, as the time difference between the actual occurrence of an event, and the subject's judgement of when the event occurred, based on their report of the clock position. A negative judgement error indicates anticipatory awareness of the event, and a positive judgement error indicates delayed awareness. The time of voluntary actions was defined as the moment of keypress closure. The time of involuntary TMS-induced movements was defined as the onset of that subject's averaged MEP. The mixed blocks were forked for the purposes of analysis into voluntary action trials and involuntary movement trials, according to whether the subject "beat" the TMS or vice versa.

Judgement errors for different events cannot be straightforwardly compared (Haggard et al., 2002). Therefore, the perceived time of each event (voluntary action, involuntary movement, tone) in the single-event baseline blocks was subtracted from the perceived time of the *same* event in the experimental blocks. The resulting *perceptual shifts* represent the effect on each event of the other events that formed its context in the experimental blocks.

3. Results

Eight percent of all trials were discarded, for reasons such as the subject not paying attention by self report, technical failure in producing MEPs, coincidence of MEP with a voluntary action in mixed blocks. The mean judgement errors, and perceptual shifts are shown in Table 1.

Differences between judgement errors for different types of event must be interpreted with caution, as physical and psychological effects cannot easily be separated. However, we note that awareness of voluntary actions is anticipatory relative to awareness of involuntary movements, replicating previous results (Haggard et al., 2002), and consistent with intentional preparation contributing part of the awareness of action.

We next analysed the perceptual shifts to investigate intentional binding. To do this, we adjusted judgements of voluntary actions, involuntary movements, and tones from the mixed blocks, by subtracting the counterpart judgements from single-event baseline blocks. This yielded four

perceptual shifts per subject. These were analysed by a 2×2 factorial ANOVA, having factors of judged event (the first event or subsequent tone), and agency (voluntary action or TMS-induced movement). ANOVA showed a borderline effect of judged event ($F(1, 7) = 5.189, p = .057$), and no effect of agency ($F(1, 7) < 1$). Most importantly, these factors interacted significantly

Table 1
Judgement errors, and perceptual shifts relative to baseline conditions

	Judged event	Mean (<i>SD</i> , range) judgement error (ms)	Mean shift from baseline (ms) (<i>SD</i> , range)
<i>Single-event baseline conditions</i>			
	Voluntary action	-1 (43, 144)	
	Involuntary MEP	58 (55, 192)	
	Auditory tone	41 (36, 127)	
<i>Unmixed conditions</i>			
Involuntary MEP, then tone	MEP	47 (53, 160)	-11 (27, 79)
	Tone	0 (33, 106)	-41 (39, 121)
<i>Mixed conditions: trials in which TMS beats subject</i>			
Involuntary MEP, then tone	MEP	47 (55, 189)	-11 (25, 66)
	Tone	3 (121, 363)	-38 (98, 293)
<i>Mixed conditions: trials in which subject beats TMS</i>			
Voluntary action, then tone	Action	29 (49, 129)	30 (24, 75)
	Tone	-37 (91, 287)	-78 (73, 225)

Both *SD* and range across subjects are given to indicate variability.

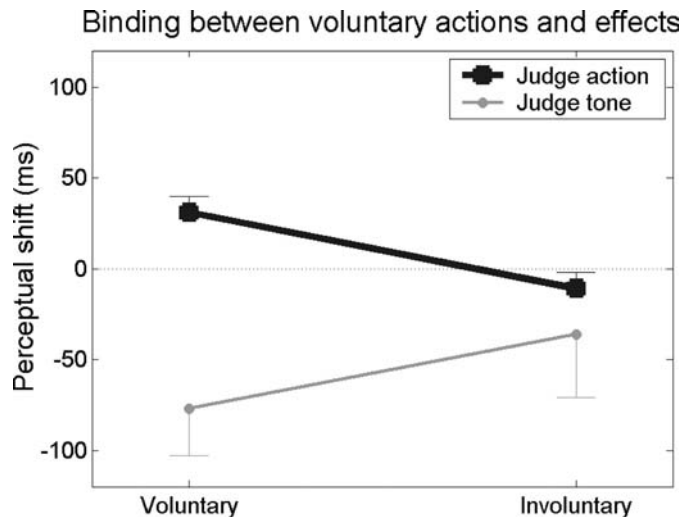


Fig. 3. Intentional binding effects. Note interaction: voluntary actions show a delaying shift towards tones, and tones an anticipatory shift towards actions. This binding is reversed for MEPs, and reduced for tones following MEPs.

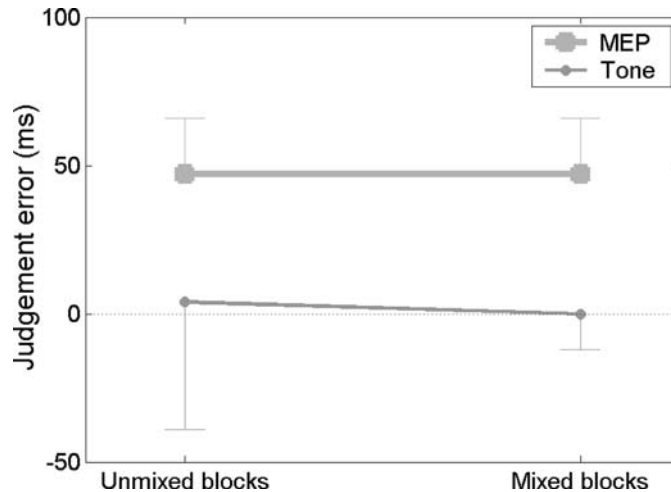


Fig. 4. Comparisons of judgement errors between mixed and unmixed blocks for MEPs and tones following MEPs. The uncompleted intentional preparation in mixed blocks does not influence awareness of MEPs or tones.

($F(1, 7) = 11.155, p < .012$). This interaction occurred because voluntary actions lead to a perceptual shift of action towards tone and vice versa, whereas these effects were reversed for TMS-induced movements, and reduced for tones following them (see Fig. 3).

To investigate whether reconstruction based on preceding but uncompleted intentions would lead to intentional binding, we performed further planned comparisons. We compared judgement errors for TMS-induced movements in mixed blocks, where subjects prepared but did not complete intentions, and for unmixed blocks, where subjects never generated intentions. There was no difference in the perceived time of TMS-induced movements between mixed and unmixed blocks ($F(1, 7) < 1$). A similar planned comparison was applied to judgement errors for tones following TMS-induced movements, in mixed and unmixed blocks. Again, no difference was found ($F(1, 7) < 1$). These null effects are numerically so small (Fig. 4) that they are unlikely to reflect low statistical power.

Finally, we compared the peak of the rectified averaged MEPs in the mixed and unmixed blocks. Because facilitation to TMS increases just prior to voluntary movement (Chen & Hallett, 1999), we predicted that MEPs in the mixed blocks, where TMS interrupted an incomplete intentional preparation, should be larger than in the unmixed blocks, where no voluntary actions were required. This prediction was confirmed (means 1.01 mV (0.20 mV *SE*) mixed, 0.81 mV (0.22 mV *SE*) unmixed, $t(7) = 2.243, p = .03$, one-tailed). The increased MEP size in the mixed blocks offers some objective evidence that subjects were indeed intentionally preparing voluntary actions even on those trials where their intention was interrupted by TMS.

4. Discussion

First, our analysis of perceptual shifts broadly replicates the effects previously reported (Haggard et al., 2002). Briefly, perceptual attraction links actions and effects in intentional

operant actions, whereas reduced binding, or perceptual repulsion occurs between physically similar involuntary movements and their effects.

Could the difference in binding between these two conditions be due to some physical difference in the events judged? In the case of the auditory tone, the answer must be “no.” Both voluntary actions and involuntary movements were followed by an identical auditory tone. Therefore, there was no physical difference between the sensory stimuli which could explain the difference in the perceived time of its occurrence. The case of the finger movement is more debatable. We took care to position the TMS coil in each subject so as to produce involuntary movements of the index finger, minimising contraction of more proximal muscles and muscles activating other digits. In both conditions, therefore, the movements selectively involved just one effector. On the other hand, the muscle activity in the two cases is necessarily different: voluntary actions produced a sustained burst of EMG activity lasting approximately 100 ms, while MEPs produced a single rapid twitch. However, this physical difference is unlikely to account for the different binding patterns of actions and MEPs, for several reasons. First, our binding estimates are based on subtracting a baseline judgement for the each event occurring in isolation. This compensates for differences in perceived time due to the different physical properties of the events. Second, in a recent study, we showed that the perceived time of MEPs can be modulated along the same lines as the perceived time of other events (Tsakiris & Haggard, 2003). In that study, the MEP was the second event in a pair, and occurred either as the somatic effect of a voluntary keypress, or following a passive displacement of the subject’s finger against the key. We showed that the MEP was bound forward in time to the voluntary action that caused it, but pushed away from the passive displacement. Thus, the perceived time of MEPs is not intrinsically any less modifiable than other events.

Our second analysis focussed on effects of mixing intention and involuntary movement. The presence of intentions in mixed blocks caused binding effect when the intention successfully produced a voluntary action, but did not cause binding when the intention was interrupted by TMS. Our interest centred on how the presence of partial, incomplete intentions in the mixed blocks might modulate the perceived time of involuntary movements and subsequent tones. If intentional binding were a reconstructive inference, made after the event, *some* intentional binding of the tone would be expected in mixed blocks. An intention to produce a tone was present, and a tone occurred, albeit by an unexpected causal route involving TMS. Nevertheless, there is a constant conjunction of relevant events. No intentional binding of the tone was in fact observed. The numerical difference between mean perceptual shifts is so small that this does seem to be a statistical power problem. Likewise preceding intentions did not influence the perceived time of TMS-induced voluntary movements, or bind them towards the subsequent tone. To summarise, intentional binding effects were seen only when actions and effects followed intentions in the normal, predictable way. When the intentional preparation was present, but did not play its normal role in causing actions and effects, binding was not seen.

Thus, at least one aspect of the conscious experience of action, the intentional binding between the perceived times of actions and their effects, does not arise from mere constant conjunction of preparation with physical movement and the intended effect. Rather, intentional binding requires a specific match between the intentional preparation, action, and effect. We suggest that temporal prediction is a particularly important part of this matching process. Preparation for action follows a clear time course, which has been measured using readiness

potentials (Kornhuber & Deecke, 1965). In an experiment by Grey Walter (cited in Dennett & Kinsbourne, 1992), the time course of these events was manipulated. Neurosurgical patients implanted with cortical electrodes pressed a button to advance a slide projector, and view a series of slides at their own pace. When the slide advance was triggered directly off the patients' readiness potential, without their knowledge, the patients reported a strong sense of surprise that the projector had anticipated the action they were about to perform. The present experiment operationalises a very similar temporal mismatch between intention, action, and effect. We could not directly trigger from the RP, as its amplitude at the scalp is low relative to the background EEG noise. Nevertheless, our random interspersing of TMS into the foreperiod for intentional preparation in mixed blocks should have effectively interrupted intentional preparation at a different phase on each trial. While we cannot specifically know how far intentional preparation had developed on any particular trial, nor whether the subject was about to act at the time TMS was applied, the observed MEP facilitation suggests that, on average, intentional preparation was occurring. The present experiment may have looser experimental control than that of Grey Walter, but it has more detailed, quantitative measures of conscious experience.

The results obtained here suggest a role of predictive models of motor control in constructing conscious experience of action. Intentional preparation involves dispatch of efference copies to internal predictive models which estimate the likely effects of the intended action (Wolpert, 1997). These efference copies appear to be generated at frontal motor areas, upstream of the primary motor cortex. Efference copies allow precise, fast motor control. We suggest they also have an important role in conscious experience, for example in regulating sensory suppression (Chronicle & Glover, 2003) in determining the perceived time of action (Haggard & Magno, 1999) and in binding actions to their effects, as in the present study.

Finally, our results have additional value in addressing possible reservations about Libet-style experiments. First, we found that the perceived time of involuntary movements was identical in mixed blocks, in which subjects prepared voluntary actions, and unmixed blocks where they did not. The mere fact of intending actions, and of attending to them did not change the perceived time of other motor events such as MEPs. In this sense, the positive effects in our experiment such as intentional binding cannot be due merely to changes in attention, general arousal level or subjective time perception associated with intending to act.

Our results then allow several conclusions about the experience of voluntary action. First, voluntary actions bind with their effects across time, while unintended, involuntary movements do not. Second, our experience of actions, and of their effects is constructed as an immediate by-product of preparation for the action, and is not a retrospective inference made after the event. Third, conscious experience of action relies on appropriate temporal and predictive relations between preparation, movement, and effect, and does not arise from a general context or loose conjunction of these events.

We agree, with Searle, that the experience of intentionality involves some causal self-reference: actions and effects are experienced in a particular way only if they are generated by the appropriate neural mechanism. A modern neuroscientist cannot believe in "free will" in Descartes' sense: conscious experience must be a consequence of brain activity rather than a cause of it. However, there is a dramatic difference between constructive and reconstructive views of conscious intention. On the constructive view, conscious experience of action is an important aspect

of neural activity, which can be studied scientifically. On the reconstructive view, it is essentially a retrospective illusion. The results of this experiment favour the constructive view.

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