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Awareness of somatic events associated with a voluntary action

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Abstract How does the brain distinguish actions that we perform from movements imposed on us? To study links between the representations of actions and their somatosensory consequences, we compared the perceived times of voluntary actions or involuntary movements and of a subsequent somatic effect (a TMS-induced twitch of the right index finger). Participants perceived voluntary actions as occurring later and their bodily effects as occurring earlier in the agency context, compared to single-event baseline conditions. When the voluntary action was replaced by a passive, involuntary movement this attraction effect reversed. In a second experiment, subjects rated the intensity of the same TMS-induced somatic effect, again following a voluntary action or a passive movement. When the somatic effect was caused by a voluntary action, it was perceived as significantly less intense than when it followed a passive movement. Our results suggest a binding mechanism integrating awareness of somatic consequences occurring in voluntary action. This ‘intentional binding’ mechanism might underlie the way in which the mind constructs a strong association between intentions, actions and consequences so as to generate the unique and private phenomenological experience of self-agency.

Keywords Agency · Awareness of action · Body awareness · Intention · Voluntary action

Introduction

Awareness of action and the attribution of agency are key issues in the neuroscientific study of consciousness (Decety and Grèzes 1999; Farrer and Frith 2002). Attribution of agency involves the ability to distinguish

actions and their effects which are self-generated from those generated by another source.

In the case of a self-generated action, intentions and efference copy should predict the consequent visual, auditory and somatosensory signals produced by our movements. Intentions and motor commands can thus be used to distinguish the sensory consequences of our own actions from externally produced sensory stimuli (Decety 1996, Jeannerod 1997; Wolpert 1997). As a consequence, we can refer the origin of an action to its proper agent and effectively distinguish the self from others (Georgieff and Jeannerod 1998). It has been postulated that a central monitor (Frith 1992) or an internal ‘forward model’ (Wolpert 1997) compares the predicted sensory outcome of our own actions with the actual somatosensory feedback, and that the cerebellum is involved in signalling the sensory discrepancy or similarity between the predicted and the actual sensory consequences of our movements (Blakemore et al. 2001).

In accordance with this view, somatosensory consequences of our own actions are perceived differently from identical somatosensory inputs that are externally generated (Claxton 1975; Weiskrantz et al. 1971). Numerous studies have shown that the perceptual consequences of self-generated actions are attenuated (Blakemore et al. 1998, 1999, 2000; Collins et al. 1998; Milne et al. 1988). Blakemore and colleagues (1998, 1999, 2000) have argued that the ability to predict the consequences of our own actions underlies this differential perception of identical somatosensory stimuli when self-generated compared to when externally generated. On a strong version of this view, the perceptual intensity of an event should be linearly proportional to the difference between its predicted and actual sensory consequences.

The above studies focussed on the perceived intensity of self-produced stimuli. Recently, we suggested that the predictive attribution process also links actions and their effects across time, to produce a coherent conscious experience of agency (Haggard et al. 2002a, 2002b). Briefly, voluntary actions which produced an external effect were perceived to occur *later* than voluntary

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actions which produced no effect. Conversely, external events produced by one's own voluntary action were perceived to occur *earlier* than events which occurred without agency. Thus, awareness of actions and effects showed an attraction in time towards each other, termed 'intentional binding'. This binding is thought to reflect a neuronal process underlying the representation of intentions, actions and effects. Associations between neural representations of events may also underlie operant learning in animals (Hall 1991).

In this paper, we generalise this 'intentional binding' mechanism to somatic effects. Any action involves two distinct elements: a motor command, and consequent body movements or somatic effects. The somatic effects may be complex, extended in time, and involve body parts which are not actively controlled. For example, if I use my left hand to push my right arm, the right arm moves as a somatic effect of the left hand's action. The brain's predictive attribution process should link the movement of the right arm to the voluntary action of the left hand, and not consider it as a separate action. Because somatic effects always accompany action, they offer a more ecological test of the 'intentional binding' concept than arbitrary auditory effects studied previously (Haggard et al. 2002b).

We therefore compared identical somatic effects following either voluntary actions or passive involuntary movements. To investigate whether the brain links representations of actions and somatic effects, we deliberately separated these events in time, and localised them to different body parts. Our design compares somatic effects of agentic movement to those of non-agentic movement: a voluntary action and its somatic effect is contrasted to an involuntary passive movement and an identical somatic effect. The parameters of movement were identical (a key press) across conditions, and the causal relation between the key press and the TMS pulse was also identical. Only the authorship of the action was different across conditions. We believe this is the first time that the perceived effects of voluntary actions are compared to the sensory effects following an identical movement performed passively by the same agent. Experiment 1 studied intentional binding under these conditions, while experiment 2 studied variations in perceived intensity of the somatic effect. We show that both phenomena are specific to voluntary actions.

Experiment 1

Materials and methods

Participants judged the perceived time of sensory and motor events, using a method developed by Libet et al. (1983). Twelve healthy naïve volunteers with normal or corrected to normal vision (ages 22–30 years, seven male, ten right-handed) viewed a clock hand (length 12 mm) rotating with a period of 2560 ms on a computer screen. The clock face was marked with conventional intervals (5, 10, 15, etc.). The initial clock position was random. Clock rotation was initiated by the experimenter. Participants judged the perceived

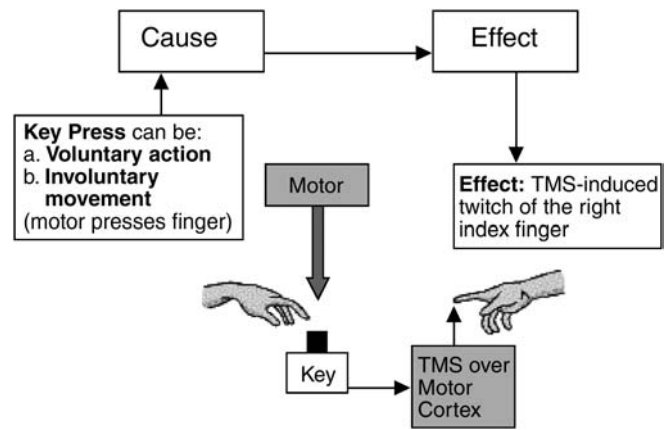


Fig. 1 The experimental set-up. A key press triggered the TMS, which was applied over the motor cortex of the participant, producing a twitch of the right index finger 270 ms later. The key was pressed either voluntarily by the participant's left index finger or by an involuntary movement (e.g. the motor was pressing the participant's finger onto the key). Participants had to judge the time onset of any of these events in different conditions (experiment 1), as well as the intensity of the TMS-induced twitch (see experiment 2)

time of onset of any of seven events according to condition, in separate blocks. A response key positioned by the left hand was connected to a transcranial magnetic stimulator (TMS) placed over the left motor cortex. Participants were informed that the key could be pressed either voluntarily or passively by the index finger of their left hand, causing a TMS-induced twitch of their right index finger. Thus, the key press was defined as the causative action, and TMS-induced twitch was the somatic effect of this action. Figure 1 shows the experimental set-up.

Participants were instructed not to press the button in a stereotyped way, to avoid acting at a fixed latency after the start of the trial, to avoid choosing to act at predecided positions of the clock hand, and to ensure that the clock rotated at least once prior to their action. Before the experiment, participants performed training blocks (ten trials per block) for the three baseline conditions. Each condition was performed in a separate block. Each participant performed the blocks in a different random order. Each block contained 31 trials, and the first trial of each block was not included in the analysis. A small number of trials (4%) had to be discarded due to technical failures or participants' failure to follow instructions.

There were three single-event baseline conditions and four operant conditions, as shown in Table 1. In the baseline conditions, only one event occurred per trial, and subjects had to judge the onset of this event. In the first baseline condition, subjects were instructed to press the key voluntarily and judge the onset of their voluntary action. In the second baseline condition, subjects were instructed that the key press would be involuntary (generated by a mechanical displacement applied by a computer-controlled motor to the subject's left index fingernail), and that they had to judge the onset of this involuntary movement. In the third baseline condition, transcranial magnetic stimulation (TMS) over the optimal location in the left motor cortex for exciting the first dorsal interosseus (FDI) of the right hand was applied under computer control, and subjects were instructed to judge the onset of the twitch of the right index finger. These baseline conditions served to establish the perceived time of each event when it occurred alone. This is required to control for individual differences in time estimation and in the division of attention between the clock and the judged events (see later).

In the four operant conditions, two events occurred per trial, an 'action' and an effect. The four operant conditions were arranged as a 2x2 factorial. The factors were the event judged by the subject

Table 1 Conditions, event judged and sensorimotor context

Condition		Event judged	Event position	Context
Single-event baseline conditions				
1	Voluntary action	Voluntary action	1	Baseline
2	Involuntary movement	Involuntary movement	1	Baseline
3	TMS-induced movement	Somatic effect	1	Baseline
Operant conditions				
4	<i>Voluntary action</i> , then TMS-induced movement	Voluntary action	1	Voluntary
5	<i>Voluntary action</i> , then <i>TMS-induced movement</i>	Somatic effect	2	Voluntary
6	<i>Involuntary movement</i> , then TMS-induced movement	Involuntary movement	1	Involuntary
7	<i>Involuntary movement</i> , then <i>TMS-induced movement</i>	Somatic effect	2	Involuntary

Table 2 Judgement errors and perceptual shifts relative to baseline conditions for experiment 1

	Judged event	Mean judgement error (ms) (\pm SD)	Mean shift (ms) (\pm SD)
Single-event baseline conditions			
Voluntary action	Action	-10 (\pm 34)	
Involuntary movement	Involuntary movement	-4 (\pm 90)	
TMS-induced movement	Somatic effect	-17 (\pm 81)	
Operant conditions			
<i>Voluntary action</i> , then TMS-induced movement	Action	16 (\pm 36)	26 (\pm 37)
<i>Voluntary action</i> , then <i>TMS-induced movement</i>	Somatic effect	-26 (\pm 86)	-9 (\pm 54)
<i>Involuntary movement</i> , then TMS-induced movement	Involuntary movement	-13 (\pm 60)	-9 (\pm 62)
<i>Involuntary movement</i> , then <i>TMS-induced movement</i>	Somatic effect	-2 (\pm 79)	15 (\pm 69)

(the 'action' or the somatic effect), and the type of 'action' producing the somatic effect (true voluntary action, or passive involuntary movement). Thus, participants had to judge (a) the onset of a voluntary action, which produced a somatic effect, (b) the onset of a somatic effect caused by a voluntary action, (c) a passive involuntary movement, which produced a somatic effect, and (d) a somatic effect caused by a passive involuntary movement. In these operant contexts, the movement of the left hand's response key triggered the TMS pulse, causing the somatic effect (twitch of the right index finger). The time interval between the action and the effect was set at 270 ms across all operant conditions. We subtracted the perceived time of each event (voluntary action, passive involuntary movement, or TMS-induced somatic effect) in the single-event condition from the perceived time of the same event in the operant conditions. This effectively controls for the prior entry phenomenon (Sternberg and Knoll 1973) and for the dynamic allocation of attention, as shown in more detail in the "Discussion" section.

TMS was delivered using a figure-of-eight coil with a Magstim 200 stimulator (Whitland, UK). The optimal location for producing twitches (MEPs) in the right IDI was located by systematically exploring a 1-cm grid over the hand area of the left motor cortex. The motor threshold (MT) was calculated 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 IDI. Thresholds ranged from 30% to 50% of stimulator output (mean, 40%). Three different TMS output levels were used throughout the experiment: 110%, 130% and 150% of relaxed motor threshold. Ten trials at each output level were used in each block. The level was changed every five trials, using a different random order of levels for each block and each subject. EMG was measured from the first dorsal interosseus (IDI) of the right hand with bipolar recording from surface Ag/AgCl electrodes, amplified and digitised at 5 kHz. Procedures were approved by the institutional ethics committee and participants gave their informed consent to participate in this study.

Results and discussion

To recap, the conditions differed according to the sensorimotor context within which the events occurred (single-event baseline or operant), and according to the event judged (voluntary action, passive involuntary movement or somatic effect). Judgement errors (defined as the difference between the actual time of occurrence of the judged event and the perceived time of its occurrence) were calculated for each trial and averaged. A negative judgement error was used for anticipatory awareness of events (the participant perceived the event happening before it really did), and a positive judgement error was used for delayed awareness (the participant perceived the event happening after it really did). The mean judgement errors and the mean perceptual shifts from the 12 participants in each condition are shown in Table 2.

Judgement errors for the three single-event conditions indicated an anticipatory awareness for voluntary action, a roughly accurate awareness of passive involuntary movement and an anticipatory awareness for TMS-induced twitch. The mean estimates for the single-event baseline conditions are comparable with previous reports (cf. Libet et al. 1983; Haggard 1999).

To control for factors such as the sensory transmission and division of attention of each participant, and differences in the salience or perceptual center of judged events, we calculated the change in the perceived time of each judged event in the operant context compared to the

Fig. 2 The pattern of perceptual shifts in experiment 1. Perceived time of voluntary action is shifted towards its effect (+26 ms), while perceived time of the effect is shifted towards the action (-9 ms). The opposite pattern is found for the involuntary movements (-9 ms) and their effects (+15 ms). The perceptual shifts are calculated by subtracting each participant's judgement error in judging the perceived time of a single event in baseline condition from the perceived time of the same event that occurred in a causal, operant condition

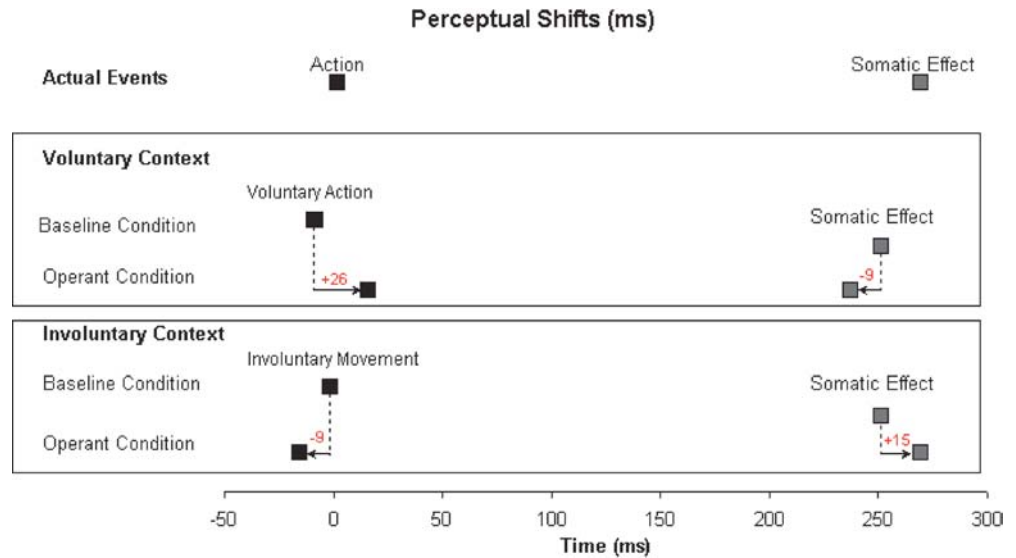


Table 3 Mean perceptual shifts (ms) across different TMS output above the motor threshold (MT)

Operant conditions	Judged event	TMS=110 (% of MT)	TMS=130 (% of MT)	TMS=150 (% of MT)
Voluntary action, then TMS-induced movement	Action	26	22	26
	Somatic effect	-34	-1	-1
Passive movement, then TMS-induced movement	Movement	3	-10	-14
	Somatic effect	4	15	41

baseline condition. These *perceptual shifts* are calculated by subtracting each participant's judgement error in judging the perceived time of a single event from the perceived time of the same event that occurred in a causal, operant context (see Table 2). Perceptual shifts represent the effect of operant context on the perceived time of each event.

Perceptual shifts between single-event and operant conditions indicated strong perceptual attraction effects between voluntary actions and their somatic effects, and strong perceptual repulsion effects for involuntary actions and their somatic effects (Fig. 2).

A voluntary action is perceived to occur 26 ms later when it produces a somatic effect than when it produces no effect. Conversely, somatic effects produced by voluntary action are perceived 9 ms earlier than somatic effects generated by computer without any preceding action. That is, voluntary actions are shifted towards their somatic effects, and somatic effects are shifted towards the actions that caused them. This pattern was reversed for passive involuntary movements. Passive involuntary movements were perceived to occur 9 ms earlier when they were followed by somatic effects than when they had no effects. Somatic effects following passive involuntary movements were perceived to occur 15 ms later than the same effects without any preceding event.

The mean perceptual shifts were subjected to factorial ANOVA, using two within-subject factors. These were the operant context (voluntary vs. involuntary) and the

type of event judged (action or somatic effect). This analysis showed no significant effect of the operant context ($F_{(1,11)}=0.242, p>0.05$), no significant effect of the event judged ($F_{(1,11)}=0.072, p>0.05$), but a significant interaction between the two factors ($F_{(1,11)}=7.226, p=0.021$). This interaction arose because voluntary context produced attraction effects between voluntary action and its somatic effect, whereas the involuntary context produced repulsion effects between involuntary action and the same somatic consequence.

Table 3 presents the mean perceptual shifts across conditions across different TMS outputs.

To investigate whether the binding effect depended on salience of the somatic effect, we also performed a three-way ANOVA on the perceptual shifts shown in Table 3, by adding the factor of TMS output level. No significant main effects were observed. The only significant effect involving TMS output level was an interaction between TMS output and event judged ($F_{(2,22)}=7.666, p=0.012$). TMS output level had a greater influence on awareness of the somatic effect than on the action, which is unsurprising. Specifically, increasing the TMS output level tended to delay the percept of the somatic effect. This effect did not interact with the type of action ($F_{(2,22)}=0.597, p>0.05$).

Our results show that operant voluntary actions elicit perceptual attraction or intentional binding effect. This effect binds together awareness of the voluntary action with awareness of its somatic effect, bringing them closer

in perceived time. An involuntary movement produced a perceptual repulsion in the opposite direction.

Experiment 2

Materials and methods

The same 12 naïve volunteers participated in this second experiment, which was tested in a separate session, shortly after experiment 1. Participants were instructed to judge the *intensity* of TMS-induced twitch of their right index finger by using a subjective scale from 1 to 10, 1 being not intense at all, 10 extremely intense. Subjects were told that the TMS-induced twitches would be similar in intensity to the ones experienced in the first experiment, so as to provide an anchor. TMS output was 110%, 130%, and 150% above the relaxed motor threshold. This second experiment consisted of three conditions. In the first control condition, participants judged the intensity of a TMS-induced twitch of their right index finger (TMS was triggered by the experimenter). In the second condition, participants judged the intensity of a TMS-induced twitch which they elicited themselves by a voluntary key press. In the third condition, participants judged the intensity of a TMS-induced twitch following a passive involuntary key press. As in experiment 1, the two experimental conditions differed according to the sensorimotor context (voluntary action vs. passive involuntary movement). As in experiment 1, the voluntary action or passive involuntary movement were performed with the left hand, and the somatic effect was experienced in the right hand, separated by 270 ms. Other aspects of method were as in experiment 1.

Results

Peak to valley MEP size was measured for each trial. Mean subjective intensity ratings and mean MEP sizes across conditions are shown in Figs. 3 and 4 respectively.

Because we were principally interested in the effect of agency, we focused on the comparison between the voluntary and the involuntary conditions. However, the fact that MEPs were largest in the single event control condition rules out the possibility that the somatic effect was facilitated by any spread of neural activation associated with the action of the left hand. The mean ratings were subjected to factorial ANOVA, using two within-subject factors. These were the operant context (voluntary vs. involuntary) and the TMS output used (110%, 130%, 150%). Unsurprisingly, the TMS output had a significant effect on the rating ($F_{(2,22)}=74.6$, $p=0.000$). More interestingly, the main effect of sensorimotor context was also significant ($F_{(1,11)}=8.067$, $p=0.016$), suggesting that the somatosensory consequences generated by a voluntary action are perceived as less intense than when they follow a passive involuntary movement. However, no significant interaction between these two factors was found ($F_{(2,22)}=0.988$, $p>0.05$), suggesting that TMS strength modulates the perceived intensity equally in both conditions. This result suggests that voluntary action reduced perceived intensity of somatic effects by a fixed amount, rather than attenuating them in proportion to their size, in the manner of a linear gain coefficient.

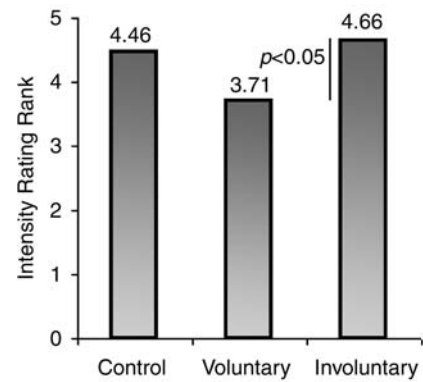


Fig. 3 Subjective Intensity Rating across conditions

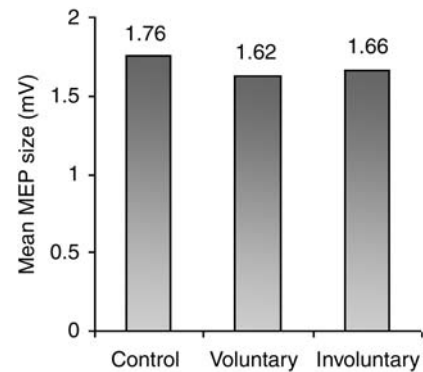


Fig. 4 Mean MEP size across conditions

To investigate whether these results could arise from a reduction in actual MEP size, we analysed the mean MEP size using the same factors. As predicted, the effect of TMS output level was highly significant ($F_{(2,22)}=74.811$, $p=0.000$). The effect of operant context was not significant ($F_{(1,11)}=0.58$, $p>0.05$), but the interaction of the two factors was significant ($F_{(2,22)}=5.643$, $p=0.006$). The interaction arose because MEPs were slightly larger after voluntary action than after involuntary action at the middle level of TMS output. In brief, the physical variation in MEP size could not explain the changes in intensity rating.

The analysis suggests that the differences in ratings are due to the different sensorimotor context (voluntary vs. involuntary) and not due to differences in the MEP size or the TMS output. Identical somatosensory consequences are perceived as less intense when caused by a voluntary action than when caused by an involuntary movement, suggesting that subjective intensity of a somatic effect is modulated by a self-generated action.

Relation between perceived intensity and MEP size

Previous studies have either used a single, unvarying somatosensory stimulus, or have not precisely quantified the stimulus used. In contrast, we were able to investigate

the relation between intensity ratings and MEP size, using a dummy regression technique (Kleinbaum et al. 1988). For each subject, intensity rating was predicted from MEP size, and a dummy variable coding the comparison between voluntary action and passive involuntary movement conditions. The coefficients of the dummy variable represented how the effect of agency modulated the slope and the intercept of the psychophysical relation between intensity and MEP size. The coefficients were compared to 0 using two-tailed t -tests. We found a significant effect on the intercept of the psychophysical relation, with significantly lower perceived intensity after voluntary action than after passive involuntary movement (dummy coefficient 1.19 ± 0.50 SE, $t_{(11)} = -2.391$, $p = 0.036$). However, the slope coefficients did not differ significantly between voluntary and involuntary condition (0.26 ± 0.27 SE, $t_{(11)} = 0.958$, $p = 0.359$). Therefore, we concluded that agency shifts the perceived intensity of all subsequent somatic effects by a fixed amount, but does not attenuate percepts in the manner of a gain. This analysis confirms a similar finding from the previous ANOVA analysis (see above).

Perceptual shifts in time and intensity judgements

In a final exploratory analysis we combined the time and intensity judgements from the two experiments in a multivariate analysis, with a single factor of operant context (voluntary action vs. involuntary movement). This analysis aimed to show whether agency effects were more pronounced on time or on intensity judgement. There was a significant difference between perceptions of somatic effect after voluntary action and after passive movement ($F_{(2,10)} = 5.37$, $p = 0.026$). This was expected given the univariate ANOVA results. Our interest focussed on the standardised canonical coefficients, which express the extent to which this between-condition difference is seen in the two dependent variables. The SCCs showed similar loadings on timing judgements (1.887) and on intensity judgements (1.478), implying that both these dimensions of perception may be modulated to an equivalent extent by agency context. We suggest that the perceptual shifts observed in time and intensity perception are consequences of a common mechanism constructing the experience of agency.

Taken together, our experiments suggest that operance has distinct and independent effects on the intensity and the timing of sensory experience. In experiment 1, operant actions and passive movements had differentially influenced the perceived time of a somatic effect. Although we did not measure subjective intensity of somatic effects directly in experiment 1, we found no interaction between the effects of agency and the objective intensity of the TMS pulse eliciting the effect. This makes it unlikely that changes in subjective timing are an artefactual consequence of changes in subjective intensity or vice versa. In experiment 2, we directly measured a reduction in subjective intensity of the identical somatic effect in

voluntary operant action, compared to passive involuntary movement. Moreover, a between-subjects comparison showed comparable effects of agency on both subjective timing and subjective intensity. We conclude that the brain's processes of agency independently construct the timing and the intensity of conscious experience. Future research might investigate the independence of these two processes further, by trying to identify experimental factors that influence timing but not intensity estimates, or vice versa.

Discussion

We first briefly consider four possible artefactual explanations of our results from experiment 1. First, previous studies of temporal awareness of action (Libet et al. 1983) have been criticised (Breitmeyer 1985) because of the prior entry phenomenon (Sternberg and Knoll 1973). In prior entry, an event on an attended perceptual stream seems to occur earlier than a synchronous event on an unattended stream. The participants presumably divided attention between the clock and the events they judged. Therefore, any single estimate of judgement error depends on the precise division of attention, which is unknown. However, the design of the present experiment involves *differences* in judgement error between baseline, single-event and operant conditions, and it requires only comparable division of attention in both conditions. Full discussion of this argument can be found elsewhere (Haggard et al. 2002a). Second, could the presence of the first event (voluntary action or passive movement) cause *dynamic* reallocation of attention to the somatic effect, producing a difference in prior entry bias between baseline and operant conditions? This suggestion cannot explain why perceptual shifts operate in opposite directions for voluntary actions and for involuntary passive movements. Third, physical differences in movement cannot account for the different pattern of results across conditions. MEP sizes were not significantly different between conditions. The key press was under identical computer control across all the involuntary conditions, and appeared similar (though not quantitatively measured) across all the voluntary conditions. Thus, we did not find reliable physical differences between the parameters of movement in single-event and operant conditions that could convincingly explain the pattern of perceptual shifts. Fourth, a non-specific effect of TMS on timing judgement cannot account for the opposite pattern of results in the voluntary vs. involuntary conditions.

Simple artefactual explanations cannot account for the pattern of perceptual shifts shown in Fig. 2. Our results show that only voluntary actions elicit intentional binding. When an intentional voluntary action is performed, awareness of the action is bound with awareness of its bodily consequences, bringing the two events closer in perceived time. A passive involuntary movement produces a perceptual repulsion in the opposite direction.

The present results provide support for the existence of a CNS process that operates only when a subject is the active agent of her actions. This ‘intentional binding’ mechanism might underlie the way in which the mind constructs a strong association between intentions, actions and consequences so as to generate the unique and private phenomenological experience of self-agency. The present study adds several additional facts to our knowledge of this process. We showed that the binding process works with a different, and more ecological modality of effect (i.e. somatomotor) than previous studies. Second, it does not work with involuntary movements and their identical somatic effects. The binding mechanism is engaged by intention, but not by mere body movement. The results reported here suggest that the function of this ‘intentional binding’ mechanism cannot be dissociated from agency.

The results from experiment 2 also recall previous studies. Blakemore et al. (1999) found lower perceived intensity for self-generated stimuli than for externally imposed stimuli. We replicated this result, with the additional control that our somatic effects were *always* preceded by a physical identical movement. Our design shows that reduction in somatic sensation is due to the intentional agency of the generating movement, not the existence of a prior movement per se. Blakemore et al. (1999) further suggested that the attenuation they observed is proportional to sensory discrepancy, or the error between the sensory feedback predicted by the forward model and the actual sensory feedback produced by the movement. We call this the ‘proportionality hypothesis’.

Our observation of both perceptual attraction and repulsion effects in experiment 1 might initially seem consistent with the proportionality hypothesis. The perceptual repulsion between passive involuntary movements and their somatic effects might reflect the operation of an inverse binding, whose function is to separate in time, and thus to discriminate, pairs of events that cannot be attributed to our own causal agency. A single neural mechanism, based on a predictive forward model, could generate a range of conscious experiences varying along a continuum from perceptual attraction to perceptual repulsion. The shift in awareness could be directly proportional to the discrepancy between predicted and actual sensory events in the forward model. Since the sensory discrepancy is not calculated until *after* delayed feedback is available, this view has the interesting implication that the awareness of our actions is reconstructed *post hoc*, rather than generated as part of the process of intending (Libet et al. 1983). Recent work on awareness of action provides evidence in favour of both real-time (Haggard and Magno 1999) and post hoc (Wegner and Wheatley 1999) views.

In the present experiments, the sensory discrepancy was additionally varied by the TMS output level. Subjects’ best estimate of the somatic effect presumably involves a typical MEP. If awareness is reconstructed based on sensory discrepancy, shifts in perceived time (experiment 1) or perceived intensity (experiment 2) of the somatic effect should be proportional to the size of the

MEP. However, no such proportional effects were found. In experiment 1, shifts in perceived time were not proportional to MEP size. In experiment 2 dummy regressions showed that voluntary action adjusted the offset level (intercept) but not the gain (slope) of perceived MEP intensity. Our data offer no support to a *proportional* relation between awareness and sensory discrepancy. Instead, our data suggest that intention acts as a general context for awareness, shifting perceived time and perceived intensity by fixed amounts. This context effect could be applied predictively, as soon as the intention is formed, rather than post hoc. Some additional element of a forward model, other than simple sensory discrepancy, could perhaps account for awareness.

The binding mechanism studied in this paper would distinguish the effects of our own actions from the effects of others’ actions and even from the effects of our own involuntary movements. This mechanism would safeguard the coherent experience of our own agency. However, in brain-damaged patients or in cases of abnormal awareness of action, the ability to correctly recognise intentions, actions and their effects is often disturbed, along with the ownership of body parts, as shown in cases of ‘anarchic hand syndrome’ (Hari et al. 1998), somatoparaphrenia (Bottini et al. 2002) and schizophrenia (Daprati et al. 1997; Fournier et al. 2001; Franck et al. 2001). In the ‘anarchic hand’ syndrome, patients report an incongruity between their intentions and the movements of the ‘anarchic hand’. For these patients, there is a phenomenological dissociation between the action and the body part performing the action, since the hand that moved is acknowledged as theirs, whereas the action is not, since they never had the conscious intention of acting in the way the ‘anarchic hand’ moved (Hari et al. 1998). In somatoparaphrenia, patients believe that their limbs contralateral to the side of the lesion belong to someone else, and the disorder is often accompanied by the inability to feel tactile sensations in the ‘non-belonging’ part of the body. Bottini and colleagues (2002) reported a case of a patient with somatoparaphrenia in whom dense tactile imperception in the left hand dramatically recovered when she was instructed to report touches delivered to her niece’s hand, rather than to her own hand. Through this verbal instruction, the mismatch between the patient’s belief about the ownership of her left hand and her ability to perceive touch on it was transiently recomposed, suggesting that ‘somatosensory awareness involves a crucial contribution from a higher-level representation of the body, including basic beliefs, such as ownership’ (Bottini et al. 2002). Many schizophrenic patients describe passivity experiences in which actions are made for them by external agents rather than by their own will (Frith 1992; Frith et al. 2000). The phenomenology of the passivity experiences reported from schizophrenic patients might be similar to the involuntary conditions (i.e. passive agency) used in the experiments reported. Recent studies of recognition of action in schizophrenics (Franck et al. 2001) suggest that schizophrenics may use the same

mechanism for recognising their own actions as normal subjects, but with an abnormal *criterion* of agency. Normal subjects accept agency for visual reply of a movement shown up to 150 ms after they made a similar movement, while schizophrenics accepted agency at delays of up to 300 ms.

In conclusion, the perceived timing and the perceived intensity of somatic effects following a voluntary action are shifted. These shifts are not found following passive involuntary movement. The shifts suggest changes in the bias or offset level of a psychophysical coupling, and were not proportional to sensory discrepancy between predicted and actual sensory feedback. We suggest that this shifting is due to intentional agency per se. It may reflect a contextual modification of awareness, and need not involve the function of a parametric forward model. We speculate that an intentional binding mechanism in the CNS underlies these effects.

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