Voluntary action and conscious awareness

Patrick Haggard, Sam Clark and Jeri Kalogeras

Institute of Cognitive Neuroscience, University College London, 17 Queen Square, London WC1N 3AR, UK
Correspondence should be addressed to P.H. (p.haggard@ucl.ac.uk)

Published online: 18 March 2002, DOI: 10.1038/nn827

Humans have the conscious experience of 'free will': we feel we can generate our actions, and thus affect our environment. Here we used the perceived time of intentional actions and of their sensory consequences as a means to study consciousness of action. These perceived times were attracted together in conscious awareness, so that subjects perceived voluntary movements as occurring later and their sensory consequences as occurring earlier than they actually did. Comparable involuntary movements caused by magnetic brain stimulation reversed this attraction effect. We conclude that the CNS applies a specific neural mechanism to produce intentional binding of actions and their effects in conscious awareness.

© 2002 Nature Publishing Group http://neurosci.nature.com

Normal human experience consists of a coherent stream of sensorimotor events, in which we formulate intentions to act and then move our bodies to produce a desired effect. Our experiences of voluntary action arise from several distinct stages of neural activity, including motor preparation[1], specification of motor commands[2] and sensory feedback from actual body movement. The CNS must bind together these representations to produce coherent experience of our own action.

One research tradition, action monitoring, has focused on the special case of action–effect mismatch. The perceived effects of actions are manipulated so that they do not match the subject's intentions[3]. Mismatches produce a distinctive conscious experience and a characteristic brain activation including the frontal lobes[3]. Temporal mismatch between actions and their effects seems particularly important in conscious experience[4] and in attribution of actions to agents[5].

A second research tradition has asked subjects to report the perceived time of their own intentions or actions[1,2], relating these subjective events to objective physiological events, such as the onset of EEG readiness potentials (RPs) or muscle activity. This tradition focuses on timing as a crucial aspect of conscious experience. When subjects use a clock hand to estimate the time at which they first experienced the conscious intention that led to a voluntary action, conscious awareness of intention lags the onset of RP[1], raising a challenge for the traditional Cartesian concept of conscious free will. Other studies suggest that awareness of intentions depends on the motor action subsequently performed. Thus, awareness of intention covaries with the lateralization of the RP to the hemisphere opposite the hand subjects choose to use, rather than with earliest onset of the bilateral RP[2]. Awareness of actions is partly generated before dispatch of the motor command from the motor cortex[6]. These latter findings suggest that awareness of intentional action arises by integrating representations from multiple stages along the chain from first intention to the action's subsequent effect, consistent with the binding process hypothesized above. Reaction-time studies have also supported a common coding mechanism that integrates representations of actions and their effects[7,8]. Nevertheless, the mechanism that binds these events remains unclear.

To study links between these representations, we first compared the perceived times of voluntary actions with the perceived times of involuntary movements induced by transcranial magnetic stimulation (TMS). We then examined how the perceived times of these events shifted when such events triggered an auditory stimulus. We studied these perceptual shifts for evidence of a binding mechanism integrating awareness of events occurring in voluntary action. We found that voluntary actions and their effects are attracted together across time, whereas shifts in the opposite direction occur when an involuntary movement is followed by the same effect.

Results

Subjects were asked to watch a conventional clock face and to judge the onset times of four events, initially presented alone. In the voluntary condition, they pressed a key at the time of their choice. In the TMS condition, they noted the time of a muscle twitch produced by stimulation of the motor cortex. In the sham TMS condition, they noted the time of an audible click made by TMS applied to the parietal cortex, which did not produce motor activation. In the auditory condition, they noted the time of a tone.

Judgment errors for these four single-event, baseline conditions (**Table 1**) indicated a roughly accurate awareness of the voluntary action, delayed awareness of the involuntary TMS-induced twitch, and intermediate values for sham TMS and for auditory tones. We did not compare these judgment errors statistically, because they relate to very different physical events, which may vary in duration, salience and other factors.

In the operant conditions, voluntary action, motor cortical TMS and sham TMS were followed 250 ms later by the tone. The presence of an additional event in the operant context caused large perceptual shifts, whose size and direction varied across conditions (**Table 1**). Perceptual shifts between single-event (baseline) and operant conditions indicated strong perceptual attraction effects for voluntary actions and consequent tones (**Fig. 1**, left).

© 2002 Nature Publishing Group http://neurosci.nature.com

Table 1. Judgment errors and shifts relative to baseline conditions for experiment 1.

	Judged event	Mean error ± s.d. (ms)	Mean shift (ms)	Change in s.d from baseline (ms)
Single-event baseline conditions				
	Voluntary action	6 ± 66		
	Involuntary MEP	83 ± 83		
	Sham TMS	32 ± 78		
	Auditory tone	15 ± 72		
Operant conditions				
Voluntary action, then tone	Action	21 ± 57	15	–9
	Tone	–31 ± 71	–46	0
MEP, then tone	MEP	56 ± 72	–27	–10
	Tone	46 ± 89	31	17
Sham TMS, then tone	TMS	25 ± 76	–7	–1
	Tone	7 ± 80	–8	8

Awareness of the voluntary key press action was shifted later in time, toward the consequent tone, whereas awareness of the tone was shifted earlier in time, toward the action.

Involuntary, TMS-induced movements produced perceptual shifts in the opposite direction (**Fig. 1**, right). Awareness of involuntary, TMS-induced movements was shifted earlier in time, away from the tone, whereas awareness of the consequent tone was shifted later in time, away from the TMS-induced movement. The results for sham TMS show minimal perceptual shifts (**Fig. 1**, center), suggesting that no binding occurs for arbitrary unrelated events.

Repeated-measures ANOVA of the perceptual shifts revealed no significant main effects of action type (voluntary action, involuntary TMS-induced twitch, sham TMS, $F_{2,16} = 0.775$, $p = 0.477$) or of event judged (operant event, tone, $F_{1,8} = 0.001$, $p = 0.975$). However, there was a significant interaction between these two factors ($F_{2,16} = 4.920$, $p = 0.022$), shown by the crossover effect in Fig. 1.

We wondered whether a dynamic reallocation of attention could explain this pattern of perceptual shifts. If subjects reduced their attention to an event, variability of judgments across trials should have increased, relative to a baseline condition. The standard deviations of judgment error across trials (**Table 1**) were therefore analyzed in the same way as the perceptual shifts in mean judgment error. An ANOVA showed no significant effect of action type ($F_{2,16} = 1.660$, $p = 0.477$) and a trend for variability to decrease for the first event and increase for the tone ($F_{1,8} = 4.399$, $p = 0.069$). Importantly, these effects did not interact ($F_{2,16} = 1.432$, $p = 0.268$). Although some (nonsignificant) variability changes did occur, for example for tones following involuntary TMS-induced movement and sham TMS, the overall pattern of variability changes is not consistent with an attentional explanation for the perceptual shifts of Fig. 1.

We also investigated whether differences in motor output could explain our awareness results, by measuring electrical activity in the muscle directly by electromyogram (EMG). We compared peak EMG amplitude and EMG attack (interval between EMG onset and resulting key press). EMG amplitude was larger with the tone (mean, 0.1428 mV) than without it (0.1388 mV). EMG attack occurred earlier with the tone (–78.6 ms, relative to key press) than without it (–76.2 ms). Delayed action awareness in operant conditions therefore was not due to sluggish motor output. For involuntary twitches, we measured the latency and peak amplitude of motor-evoked potentials (MEPs), brief EMG pulses caused by TMS. MEP latency was slightly greater with the tone (22.0) than without it (21.6 ms). MEP amplitude was nonsignficantly greater with the tone (1.04 mV) than without it (0.84 mV, $p = 0.26$). However, such changes of MEP size do not necessarily alter perceived timing (data not shown). The anticipatory shift in awareness of involuntary movements with the following tone is thus unlikely to reflect changes in MEPs.

In a second experiment, we investigated effects of temporal interval on intentional binding. Twelve new student subjects performed voluntary key presses, followed by a tone at intervals of 250, 450 or 650 ms. Subjects judged the time of tone onset, both in separate fixed blocks in which all trials involved a single interval and in three additional blocks containing a randomized combination of all intervals. Fixed and randomized blocks were tested in counterbalanced halves of the experiment. A single-event, baseline block of tone-only trials was measured in each half and used to calculate perceptual shifts as before (**Table 2**).

An ANOVA on shifts in judgment revealed significant effects of schedule ($F_{1,11} = 6.659$, $p = 0.026$) and of lag ($F_{2,22} = 15.607$, $p < 0.001$) and a significant interaction ($F_{2,22} = 3.958$, $p = 0.034$). An ANOVA on the changes in variability across trials showed no

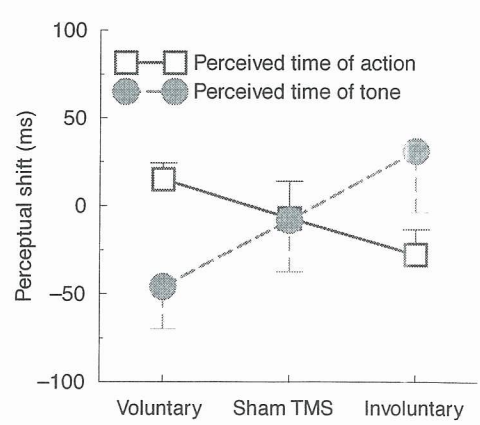

Fig. 1. Pattern of perceptual shifts shows a binding effect for voluntary actions, but not for involuntary movements. Each subject's mean judgment error in the appropriate single-event baseline condition was subtracted from the mean judgment error for the corresponding event in the operant condition. Negative perceptual shifts indicate that an event is perceived earlier in an operant context than in the baseline condition. Binding of the first event toward the consequent tone is therefore shown as delayed awareness of the operant event and anticipated awareness of the tone. Left, voluntary actions produce binding effects. Awareness of voluntary action shifts later toward a consequent tone (□), whereas awareness of the tone shifts forward toward the voluntary action that evokes it (●). Middle, neutral events such as sham TMS produce minimal perceptual shifts. Right, involuntary movements (TMS-induced MEPs) do not sustain binding, but produce repulsion effects in the opposite direction. Awareness of the MEP is shifted earlier, away from the consequent tone (□), whereas awareness of the tone is shifted later, away from the MEP (●). Error bars, standard error across 9 subjects. Repeated-measures ANOVA interaction between judged event and operant context is significant ($p = 0.022$).

significant effect of schedule ($F < 1$), a trend toward an effect of lag due to increased variability at 450 ms only ($F_{2,22} = 15.607$, $p < 0.094$), and no significant interaction ($F < 1$). These results suggest a binding effect that correlates with temporal contiguity, and temporal predictability, but seems not to depend simply on improved allocation of attention at the time of the effect.

Table 2. Judgment errors for auditory tones and shifts relative to baseline for experiment 2.

Schedule	Operant interval (ms)	Mean error ± s.d. (ms)	Mean shift (ms)	Change in s.d. (ms)
Single-event baseline condition				
Fixed	(tone only)	−6 ± 64		
Randomized	(tone only)	−21 ± 65		
Operant conditions (voluntary action, then tone)				
Fixed	250	−103 ± 67	−97	3
Fixed	450	−40 ± 71	−35	7
Fixed	650	−16 ± 56	−11	−8
Randomized	250	−53 ± 68	−32	3
Randomized	450	−17 ± 80	4	16
Randomized	650	−5 ± 67	16	2

Discussion

Our results show that truly operant intentional actions elicit perceptual attraction or binding effects. This effect associates or binds together awareness of the voluntary action with awareness of its sensory consequence, bringing them closer in perceived time. Mere peripheral body movements, of the kind produced by motor cortical TMS, produce a perceptual repulsion in the opposite direction. Arbitrary co-occurring events, such as the click of sham TMS and the consequent tone, elicit no perceptual shifts.

We first consider possible artifactual explanations of our results. Previous studies of awareness of action[1] have been criticized[9] because of an attentional bias, known as prior entry, in timing judgment tasks[10]. In prior entry, an event on an attended perceptual stream seems to occur earlier than a synchronous event on an unattended stream. Our subjects presumably divided attention between the clock and the events they judged. Any single estimate of judgment error therefore depends on the precise division of attention, which is unknown. However, recent estimates of prior entry bias amount to only 12 ms[11], much less than the effects reported here. The traditional value of around 50 ms for prior entry bias[10] may be confounded by response biases[11]. More importantly, our approach involves differences in judgment error between single-event and operant conditions, and requires only comparable division of attention in both conditions. Allocation of attention should be comparable for the first event of an operant context and for the same event in a single-event, control condition.

A more sophisticated objection involves the dynamic reallocation of attention. The presence of the first event could cause allocation of attention to the subsequent tone to differ between the operant condition and the baseline, tone-only condition, which might in turn influence the perceived time of the tone. The minimal perceptual shifts in our sham-TMS condition show that the number of events, and the contingent relationship of the second event to the first, do not bias timing judgments. Finally, analysis of variability across repeated judgments gave some evidence regarding dynamic shifts of attention in our data. We found no evidence that our subjects dynamically shifted attention away from the voluntary action and toward its effects in operant situations. Moreover, there is no simple pattern of reallocation of attention consistent with the overall pattern of both the mean perceptual shifts and the variability changes in our data (**Table 1**). We did find a (nonsignificant) increase in variability above baseline in the specific case of tones following MEPs, together with a perceptual delay for the tone (**Fig. 1**). However, an earlier study of awareness of manual reactions following MEPS[6] found perceptual anticipations, rather than the delays observed here, suggesting that TMS does not itself produce a perceptual delay. Finally, reallocation of attention presumably takes time, in which case any prior entry effect should increase as the interval between action and effect increases; our second experiment showed that the opposite was the case. We therefore believe reallocation of attention and prior entry cannot explain our overall pattern of results.

Studies using very different tasks show that both cortical activity and intensity of subjective experience are lower for self-induced sensory effects than for comparable externally imposed stimuli[4,12], suggesting that the effects of our voluntary movement may be attenuated. In addition, 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 awareness shifts. Finally, any simple artifactual explanations cannot easily account for the crossover pattern of perceptual shifts in Fig. 1. Simply realigning a subjective zero time earlier or later, as in classical prior entry, would not produce perceptual shifts in opposite directions for the first event and for the consequent tone. Simply speeding up or slowing down an internal clock for subjective timing would not produce shifts in opposite directions for voluntary and involuntary contexts. Finally, a nonspecific effect of TMS on timing judgment cannot explain either the absence of effects in the sham condition or the different effects on the involuntary movement and on the consequent tone. Thus simple artifactual explanations are unable to account for the crossover interaction found in our results: an active binding process is required.

We therefore conclude that conscious representations of sensorimotor events surrounding voluntary action are bound by a specific cognitive function of the CNS. Our second experiment suggests that this function obeys two important general principles of association. The binding effect is modulated by temporal contiguity and temporal predictability. These results suggest that these perceptual shifts may be a conscious aspect of a general linkage through time between representations of actions and effects. Accordingly, we refer to this function as intentional binding.

The finding of perceptual repulsion for involuntary movements is also interesting. We speculate that it reflects a mental operation to separate in time, and thus to discriminate, pairs of events that cannot plausibly be linked by our own causal agency. This repulsion could be due to the unexpected and surprising quality of TMS-induced movement and may be the conscious correlate of repudiating agency.

The intentional binding process fits well with recent models of action–effect matching, both in neuropsychiatry and in computational motor control. Such matching processes typically induce motor learning, but also produce a characteristic conscious experience, particularly when a mismatch occurs[13]. Schizophrenic patients with hallucinations and delusions may attribute external events to their own agency[5] or may attribute their own actions

© 2002 Nature Publishing Group http://neurosci.nature.com

© 2002 Nature Publishing Group http://neurosci.nature.com

to external sources[14]. We speculate that these misattributions may reflect excessive or impoverished intentional binding, respectively. Moreover, matching motor commands with sensory consequences of movement via a forward model may underlie fast and efficient motor control[15]. Previous studies suggest awareness occurs when sensory events cannot be predicted by forward models[3]. Our results suggest that a forward model process could also contribute to normal conscious awareness, in respect to perceived timing of actions and effects. Specifically, we observed binding of conscious representations of actions and effects only in the case of true intentional agency, in which the subject's motor commands cause the subsequent effect. We speculate that our intentional binding effects reflect normal agency, whereas the experience of surprising mismatch[3,5] may correspond to the perceptual repulsion that we observed for involuntary, TMS-induced movements. Taken as a whole, these results suggest that the brain contains a specific cognitive module that binds intentional actions to their effects to construct a coherent conscious experience of our own agency.

Methods

In a variant of previous methods[1], nine right-handed healthy naive subjects (ages 25–54) viewed a clock hand (length 12 mm) rotating with a period of 2,560 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 subject pressing a key on a computer keyboard with the left hand. In single-event baseline conditions, subjects judged the onset time of one of four events, presented in separate blocks. In the voluntary action condition, subjects made a right index-finger key press at a time of their own choice, and judged the time at which they pressed the response key. They were instructed to avoid responding in a stereotyped way, at a predecided clock time, or during the first rotation of the clock hand. In the TMS-induced, involuntary movement condition, transcranial magnetic stimulation produced involuntary twitches of the right hand, and subjects judged the onset of the twitch. In the sham-TMS condition, TMS was delivered over left parietal cortex, 7 cm posterior to the motor cortical TMS site. This produced an audible click, but no recordable muscle activity or abnormal perceptual experiences. Subjects judged the onset of the click. In the auditory-stimulus condition, subjects heard a pure tone (1,000 Hz, 100 ms duration) over a loudspeaker. In the TMS-induced movement, sham-TMS, and auditory-stimulus conditions, stimuli occurred uniform randomly between 2.5 and 8 seconds after trial onset, approximately matching the distribution of subjects' key presses in the voluntary action condition.

The clock stopped a random 1,500–2,500 ms after the event of interest. Subjects then reported the clock position at which the designated event for that block occurred, using a computer keypad with their left hands. Subjects were encouraged to use the highest numerical precision possible, and did not restrict themselves to using the numbers marked on the clock face.

In three further pairs of operant conditions, an auditory tone followed voluntary actions, motor-cortical TMS stimuli, or sham TMS stimuli with a fixed inter-onset latency of 250 ms. The subjects could now cause the tone by their voluntary actions. The TMS events had a similar association with the tone, but did not involve agency. Subjects judged either the first event (voluntary action, sham TMS or cortical TMS) or the consequent tone in separate conditions, giving six conditions.

Each condition was tested in a separate block of 40 trials. Each subject performed the conditions in a different random order, in a single session. The mean and standard deviation of judgment error (defined as the difference between the clock positions at the judged and actual onsets of the specified event) was calculated for the trials in each condition. Anticipatory judgments were represented as negative judgment errors. We subtracted each subject's mean judgment error in the single-event, baseline conditions from the mean judgment error for the same event in the operant conditions. For example, the perceived time of a voluntary action occurring alone was subtracted from the perceived time of the same voluntary action when it was followed by a tone. Likewise, the perceived time of the tone occurring alone was subtracted from the perceived time of a tone elicited by the subject's voluntary action. The resulting perceptual shifts measure binding between actions and effects.

EMG was measured from the first dorsal interosseus (1DI) of the right hand with bipolar recording from surface Ag/AgCl electrodes, amplified, digitized at 5 kHz, rectified, averaged and finally smoothed (cutoff, 25 Hz) using a second-order, dual-pass Butterworth filter.

TMS was delivered using a focal coil with a Magstim 200 stimulator (Whitland, UK). The optimal location for producing twitches (MEPs) in the right 1DI was located by systematically exploring a 1-cm grid over the hand area of the left motor cortex. The motor threshold was calculated for each subject by reducing stimulator output in 5% steps to find the lowest level at which 3 MEPs exceeding 50 μV peak amplitude were obtained from 5 successive stimulations of the relaxed 1DI. Thresholds ranged from 27% to 43% of stimulator output (mean, 37%). TMS output in the experimental conditions was set at 120% of relaxed threshold. Procedures were approved by the institutional ethics committee.

Acknowledgements

This research was supported by MRC, Wellcome Trust and Leverhulme Trust. S.C. was involved in experiment 1; J.K. was involved in experiment 2.

Competing interests statement

The authors declare that they have no competing financial interests.

Received 27 November 2001; Accepted 22 February 2002

1. Libet, B., Gleason, C. A., Wright, E. W. & Pearl, D. K. Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential): the unconscious initiation of a freely voluntary act. *Brain* 106, 623–642 (1983).
2. Haggard, P. & Eimer, M. On the relation between brain potentials and the awareness of voluntary movements. *Exp. Brain Res.* 126, 128–133 (1999).
3. Fink, G. R. *et al.* The neural consequences of conflict between intention and the senses. *Brain* 122, 497–512 (1999).
4. Blakemore, S. J., Wolpert, D. M. & Frith, C. D. Why can't you tickle yourself? *Neuroreport* 11, 11–16 (2000).
5. Daprati, E. *et al.* Looking for the agent: an investigation into consciousness of action and self-consciousness in schizophrenic patients. *Cognition* 65, 71–86 (1997).
6. Haggard, P. & Magno, E. Localising awareness of action with transcranial magnetic stimulation. *Exp. Brain Res.* 127, 102–107 (1999).
7. Hommel, B. The cognitive representation of action: automatic integration of perceived action effects. *Psychol. Res.* 59, 176–186 (1996).
8. Elsner, B. & Hommel, B. Effect anticipation and action control. *J. Exp. Psychol. Hum. Percept. Perform.* 27, 229–240 (2001).
9. Breitmeyer, B. Problems with the psychophysics of intention. *Behav. Brain Sci.* 8, 539 (1985).
10. Sternberg, S. & Knoll, R. L. in *Attention and Performance IV* (ed. S. Kornblum) 629-686 (LEA, Hillsdale, New Jersey, 1973).
11. Shore, D. I, Spence, C. & Klein, R. M. Visual prior entry. *Psychol. Sci.* 12, 205–212 (2001).
12. Blakemore, S. J., Frith, C. D. & Wolpert, D. M. Spatio-temporal prediction modulates the perception of self-produced stimuli. *J. Cogn. Neurosci.* 11, 551–559 (1999).
13. Reason, J. *Human Error* (Cambridge Univ. Press, 1990).
14. Frith, C. D. *The Cognitive Neuropsychology of Schizophrenia* (LEA, Hove, UK, 1992).
15. Wolpert, D. M. & Ghahramani, Z. Computational principles of movement neuroscience. *Nature Neurosci.* 3, 1212–1217 (2000).