Consciousness and Cognition 22 (2013) 1431–1441

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

The time windows of the sense of agency

C. Farrer *, G. Valentin, J.M. Hupé

Centre de Recherche Cerveau et Cognition, Université de Toulouse UPS & CNRS, Toulouse, France

ARTICLE INFO

Article history:
Received 11 February 2013

Keywords:
Sense of agency
Time window of integration
Contextual information
Prior information

ABSTRACT

The sense of agency depends on some internal cues that derive from action control, as well as external cues like contextual information and prior information (degree of contingency between an action and is effect). We assessed whether external agency cues are combined with internal agency cues to affect the sense of agency. In two experiments participants performed a movement (button press) that elicited, after a varying delay, an effect (ball appearing on a screen), and reported their sense of agency over the effect (full, partial or no-agency) while internal cues (premotor information) and external cues (contextual and prior information) were manipulated. We assessed the effect of agency cues on the delays at which the sense of agency varied. The delays were increased with premotor signals but were decreased with contextual information. These findings favour a model of integration of internal and external agency cues over time.

1. Introduction

Our actions are often accompanied by a sense of agency, the experience of controlling our own actions and their effects. Because the implementation of an action goes through several stages (an action is first planned, then initiated and finally completed) we have access to different conscious experiences that are tied to these different steps (Gallagher, 2010; Pacherie, 2008). Among these conscious experiences, the sense of agency over an effect is of particular importance because it informs us about the appropriateness of our actions on the external world. The sense of agency over an effect specifically reflects the extent to which our actions cause effects and is determined by the spatial and temporal relationships between an action and its effect. These relationships apply to distinct types of cues related to the control of action (internal agency cues) and to the perception of its resulting effect. Internal agency cues encompass various signals that are tied to the different stages of the control of an action. These signals include internal volitional signals, the predicted sensory signals of an action that are generated by the internal models of action (Feinberg, 1978; Frith, 2005; Frith, Blakemore, & Wolpert, 2000; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005; von Holst & Mittelstaedt, 1950), as well as proprioceptive signals arising from the effector's movement (Balslev, Nielsen, Lund, Law, & Paulson, 2006; de Vignemont & Fourneret, 2004; Evans, 1982; Farrer, Franck, Paillard, & Jeannerod, 2003a; Marcel, 2003).

The sense of agency is also affected by additional external cues that do not derive from action control. For example, cognitive cues (*e.g.*, instructions, prior thoughts, beliefs) coherent with the subsequent effect can enhance the sense of agency when presented just before the onset of action (Aarts, Custers, & Wegner, 2005; Linser & Goschke, 2007; Sato, 2009; Sato & Yasuda, 2005; Wegner, Sparrow, & Winerman, 2004; Wegner & Wheatley, 1999). Likewise, implicit knowledge acquired from previous occurrences of an action and its effect and reflecting their degree of contingency (*i.e.*, the extent to which

* Corresponding author. Address: CNRS CERCO UMR 5549, Pavillon Baudot, CHU Purpan, BP 25202, 31052 Toulouse Cedex 3, France. Fax: +33 (0)5 62 74 61 17.

E-mail address: chloe.farrer@cerco.ups-tlse.fr (C. Farrer).

1053-8100/$ - see front matter
http://dx.doi.org/10.1016/j.concog.2013.09.010

an action and an effect co-occur) also affects the sense of agency (Moore, Lagnado, Deal, & Haggard, 2009; Shanks & Dickinson, 1991; van der Weiden, Aarts, & Ruys, 2011).

It, however, remains unclear whether these external agency cues are combined with internal agency cues to affect the sense of agency or whether internal and external agency cues independently affect the sense of agency. To address this question, we propose a classification of external agency signals depending on their temporal properties because we think that these properties might be a key element in understanding how these external signals affect the sense of agency. We thus distinguished between contextual signals that are time locked to the action onset (*i.e.,* they are emitted around the onset of the action) and prior information that is conveyed by signals that are not time locked to the action onset because this information is derived from the subject's past experiences.

This question makes sense within a model of the sense of agency that enables formulating predictions about the integration of internal and external agency cues over time. This model postulates that the sense of agency is the result of processes of causal perception by which an effect is perceived as causally linked to the action (Wegner & Wheatley, 1999; Wegner, 2003; Kawabe, Roseboom, & Nishida, 2013). There is clear evidence that the perception of a causal link between two external objects and the sense of agency share the same property of temporal contiguity. Increasing the delay between an action and its effect strongly diminishes the sense of agency over that effect (Farrer, Bouchereau, Jeannerod, & Franck, 2008; Knoblich & Kircher, 2004; Leube et al., 2003; Sato & Yasuda, 2005; Shanks & Dickinson, 1987, 1991; Shanks, Pearson, & Dickinson 1989). Likewise, when observing a moving object that stops close to another stationary object and the latter starts to move after a certain amount of delay, one perceives a causal relation between the two moving objects (*i.e.,* the first moving object is perceived as causing the movement of the second stationary object). But this is only the case if the second object starts to move within a specific time window (*i.e.,* within a minimum delay after the first object has stopped, Michotte, 1946, 1963). In that case, the causal perception depends on a time window within which the signals related to the two objects have to be integrated in order for the two objects to be perceived as causally linked. There is evidence that the sense of agency also depends on the integration of an action and its effect over time (Kawabe, Roseboom, & Nishida, 2013; Wolpe, Haggard, Siebner, & Rowe, 2013). Recently, Kawabe et al. (2013) have shown that the sense of agency depends on processes of temporal grouping between an action and an effect that are similar to those involved in grouping sensory signals. This led to the hypothesis that the sense of agency depends on a time window (starting from the onset of action and extending over a certain period) within which the signals related to the action (*i.e.*; internal agency cues) and to the effect (effect-related signals) have to be integrated. If the delay between an action and its effect increases, the integration of the effect with the action would be less likely because this effect would occur outside this time window; as a consequence the sense of agency over that effect would be affected. Kawabe et al. (2013) have also shown that additional external signals emitted when the action takes place affect the sense of agency by impacting the temporal grouping between an action and its effect. We further suggest that additional external agency cues that occur within the time window of integration would be combined with internal agency cues.

The present study assessed whether the sense of agency depends on the integration of an action and its effect within a time window and whether additional external agency cues affect this integration. We conducted two studies in which participants were required to perform a movement (a button press) that elicited an effect (apparition of a ball on a screen) and to report their sense of agency over that effect while the delay between their movement and the effect was varying. One major difficulty when assessing the sense of agency is to obtain measures that accurately reflect the participants' conscious experiences. Requiring participants to quantify the intensity of their agency might yield unreliable measures of agency as our agency experiences are not quantifiable in nature. Likewise, asking participants to make a self/other distinction might not be appropriate as they might feel that their actions have partially caused the effect, and therefore they might not be satisfied with a forced choice between 'self' (or full-control) and 'other' (or no-control) responses. Offering participants the additional choice of reporting a "partial control" response (in addition to full or no control) has proven to better capture the sense of agency (Farrer et al., 2003b, 2008). Participants were therefore given the choice between three responses: (full control) 'the action fully triggered the ball'; (partial control) 'the action partially triggered the ball' and (no-control) 'the computer triggered the ball'.

We also manipulated internal and external agency cues given to the subjects. Internal agency cues were manipulated by having conditions with or without premotor signals (internal volitional and predicted sensory signals). External agency cues were manipulated by having conditions with or without contextual information (a sound coherent with the action-effect) or conditions with distinct prior information (*i.e.*, distinct degrees of movement-effect contingency). Experiment 1 examined the effects of both premotor and contextual information and experiment 2 examined the effects of both premotor information and prior information.

We computed and compared the delays at which the sense of agency over an effect varied (from full control over the effect to partial control over the effect; and from partial control to no-control). We reasoned that (1) if the sense of agency depends on a time window within which the action is integrated with the effect, manipulating the internal agency cues given to the subjects (presence or absence of premotor signals) should affect the time window of integration, this would result in differences in the delays at which the sense of agency varies. (2) We also hypothesised that if external agency cues are integrated with internal agency cues over time, then the delays at which the sense of agency varies should be affected by additional external cues. (3) We further hypothesised that depending on their temporal properties; different external cues would differently affect these delays. Specifically, we tested the hypothesis that only external cues that occur within the time window can be combined with the internal agency cues. Therefore, only contextual external cues would affect the delays at which the sense of agency varies.

2. Study1: premotor information and contextual information

2.1. Participants

Twenty-one naïve participants (mean age 23.30, SD = 5.33) participated in study 1. They were right handed as assessed by the Edinburgh inventory (Oldfield, 1971) and were paid 10 euros for their participation.

2.2. Session with no contextual information

2.2.1. Materials and methods

Participants sat at a distance of 60 cm from a 17′ Iiyama master pro 454 monitor running at a refresh rate of 100 Hz, with a chin rest steadying their head, and the centre of the computer screen at eye level. Participants were required to fixate a cross (its duration randomly varied between 500 ms and 1500 ms) at the centre of the screen and to press a button box with their left index whenever they wanted once the fixation cross had disappeared. This button press triggered the apparition of a grey ball (5° in visual angle, 500 ms duration) at the centre of the screen. Stimuli were programmed using Direct X 11. The experiment involved two tasks (''active'' and ''passive'') that were counterbalanced across participants. Prior to each task, participants underwent a training session of ten trials, where the ball appeared immediately after the button press (''no delay'', that is less than 10 ms after the button press was detected by the computer). This ''baseline condition'' is important for participants to learn the temporal dynamics of the causal relationship between the button press and the apparition of the ball on the computer screen, that is the temporal relationship between this specific action and its effect in the case of full control.

In the active task, the ball appeared on the screen with a delay ranging between 0 ms and 1100 ms (14 possible equidistant delays measured with an oscilloscope). The ball was always controlled by the participants' action and appeared with a certain amount of delay. However, because the goal of this study was to assess variations in the sense of agency, participants were instructed, prior to running the task, that the ball would either be controlled by them or by the computer. They were told that either the ball would appear directly after they had pressed the button, or it would appear after a certain amount of delay, or the computer itself would control the ball and in that case they would have no control over it. We required participants to estimate on each trial what they thought happened, using three-choice responses: (1) Self: ''my button press directly triggered the ball''; (2) Delay: ''my button press triggered the ball but it appeared with a time lag''; (3) Other: ''my button press did not trigger the ball, it's the computer that triggered it.'' We named these responses respectively 'full control', 'partial control' and 'no-control' (see Fig. 1, study 1). Participants lay three fingers of the right hand on three buttons of a response box; they had to respond as rapidly as possible by pressing one of the response buttons. Response buttons were counterbalanced across participants.

The passive task was identical to the active task with the only difference that participants did not perform any voluntarily movement: their left index finger rested on the response button and the button press was caused by an electromagnet placed inside the response box. Participants were given the same instructions as in the active task and had to choose between three possible responses: ''the ball appeared immediately after the button was pressed'', ''the ball appeared with a delay after the button was pressed'' and ''the ball was controlled by the computer''. We use the term sense of control (rather than sense of agency) for referring to the participants' conscious experiences in the passive tasks. For consistency, this term is also used when we refer indifferently to the active and the passive tasks. In each task, delays were repeated ten times each and randomly varied between trials, their order of presentation differed across participants. Participants completed 140 trials in each task and they were allowed to pause at the end of each task.

2.3. Session with contextual information

The second session was identical to session 1 with the only difference that additional contextual information was given to the participants. A brief beep (75 dB, 14 ms, 416 Hz) was generated by the speakers (MS 691 Multi-Media Speaker System Stereo) and emitted at the time of the button press in both the active and passive tasks. Sound and no-sound sessions were counterbalanced across participants.

2.4. Data analyses

We aimed at estimating the delays (defined as the time interval between action and ball onsets) at which participants' responses about their sense of control over the ball varied (*i.e.,* from full-control to partial control and from partial control to no-control). We first computed the individual rates of ''full control'' responses, ''partial control'' responses and ''no-control'' responses for each delay value. These rates were computed for each task (active and passive) of each session (sound and no-sound). Non-linear functions were then fitted to the rates of each response using a least squares method, resulting in 12 regression curves (3 responses × 2 tasks × 2 sessions) for each participant. Decreasing and increasing sigmoid functions were used to fit the rates of full control and no-control responses respectively. The sigmoid function was defined as $Y = 1/(1 + (\exp(a * (x - b))))$, where a and b are free parameters. Parameter a is related to the tangent at the inflection point

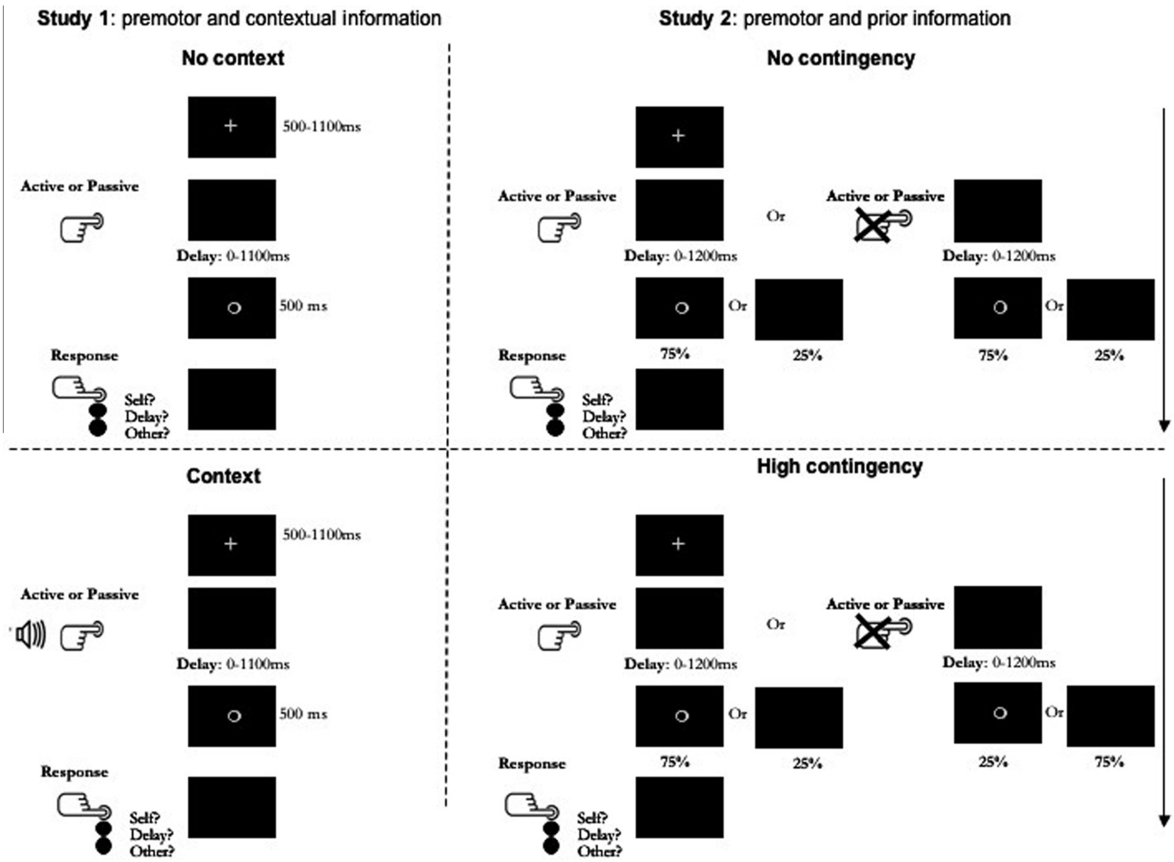

Fig. 1. Schematic representation of trials in study 1 (left panel) and study 2 (right panel). In passive trials the button press was caused by an electromagnet placed inside the response box. In study 2, the no-contingency ($\Delta p = 0$) and contingency ($\Delta p = 0.5$) blocks only differed with respect to the probabilities of conditions in which the action was absent. In the no-contingency block of the active and passive tasks the probabilities for the conditions in which there was no movement and the ball would either appear or not were 0.75 and 0.25 respectively. In the high contingency block the probabilities for these two conditions were 0.25 and 0.75 respectively.

($a < 0$ for an increasing sigmoid curve and $a > 0$ for a decreasing sigmoid curve). Parameter b corresponds to the delay value at the inflexion point. The rates of partial responses were best fitted by a non-linear function whose equation was $Y = 1 - (1/(1 + (\exp(a * (x - b))))) + (1/(1 + (\exp(c * (x - d)))))$, with a inferior to 0, b inferior to d and c superior to 0. Non-linear regressions were performed using Matlab.

The delays at which the responses about the sense of control varied were estimated from the inflexion points of the curves because this parameter is considered as the data point where there is a change in agency experiences (Sato, 2009; Shimada, Qi, & Hiraki, 2010) and it is a reliable statistic of the curve. The delays were estimated from the inflexion points of the full control and no-control sigmoid functions as the best *fits* were obtained for these curves, compared to the partial control responses curves. Furthermore only individual fits with $R^2 \geqslant 0.70$ were considered for further analyses (we excluded two participants from the analyses because of poor fit).

The delays at which participants tended to have a full-fledged sense of control over the ball ranged from 0 ms (action onset) to the delay where the full control sigmoid curve reached its inflexion point (full control delay). The delays at which participants tended to experience a partial sense of control ranged from the full control delay to the delay at which the no-control sigmoid curve reached its inflexion point (no-control delay). Finally, beyond the no-control delay participants tended to no longer have a sense of control over the ball (see Fig. 2).

The delays at the inflexion points were then compared across responses (full control and no-control), tasks (active vs. passive) and sessions (no-sound vs. sound sessions) using a $2 \times 2 \times 2$ repeated measures ANOVA. Post-hoc analyses were conducted using Fisher's LSD and further checked with Wilcoxon tests for pairwise comparisons. We used partial eta squared (${}_p\eta^2$) as our measure of effect size (Richardson, 2011) throughout and $p < .05$ was taken as the criterion for significance.

2.5. Pre-tests

To ensure that the delays were stable over time irrespective of the hand performing the action, we conducted a pre-test in which ten right-handed participants (mean age: 22.5, SD = 1.96) were required to assess whether they fully controlled the

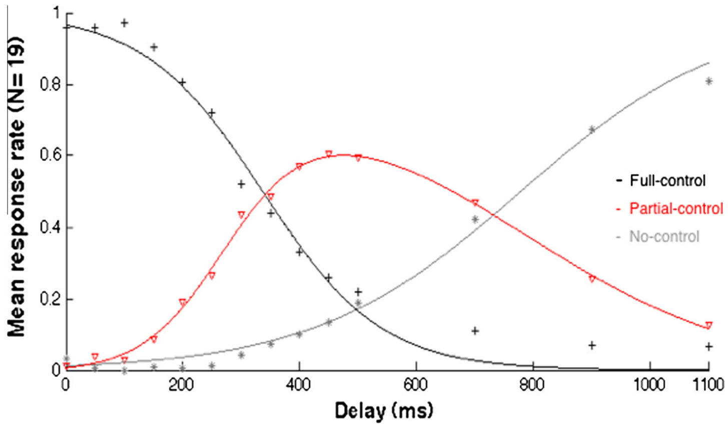

Fig. 2. Mean response rates ($N = 19$) for full-control (black), partial control (red), and no-control (grey) responses as a function of the delay (ms) in the active task for the no-sound session. For illustration purposes, here and in the next figures, we aggregated all the responses as if there was only one subject. Each data point represented therefore a single measure of response rate (no error bar). For data analysis, curves were fitted independently for each subject and condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ball. Subjects performed two sessions, one using their right hand to press the button, the other using their left hand, each session including one active task and one passive task. Delays for the ball to appear ranged between 0 ms and 350 ms and were repeated ten times each. Pairwise *t*-tests on the measured delays revealed no significant differences between the two sessions, ensuring us that the delays were stable across time and that there was no impact of the hand performing the movement.

2.6. Results and discussion

2.6.1. Delays at the inflexion points

Increasing the delay between the onset of the action and the onset of the ball resulted in participants' responses varying from full control, to partial control and to no-control (Response, $F(1,18) = 105.04$; $p < .0001$; ${}_p\eta^2 = 0.85$). Participants gave a majority of full-control responses when the ball occurred within a delay ranging between 0 and 334 ± 27 ms (mean and SE for the active task in the no-sound session); a majority of partial control responses for intermediate delays (ranging between 334 and 708 ± 42 ms); and a majority of no-control responses for longer delays (superior to 708 ± 42 ms), (see Table 1).

Importantly, the delays at which the responses varied significantly differed between the active and passive tasks (task, $F(1,18) = 11.27$; $p = .004$; ${}_p\eta^2 = 0.39$). The delays for shifting from one response to another were longer in the active condition compared to the passive condition (the means and SE of the within-participant differences between active and passive delays in the no-sound session were equal to 42 ± 25 ms for full control delays and to 80 ± 29 ms for no-control delays; see Fig. 3). Longer delays in the active task were equally observed for both full control and no-control responses as shown by the non-significant interaction between task and response (all LSD tests comparing active and passive tasks: $p \leqslant .014$; and all tests of Wilcoxon: $T(19) \geqslant 24.00$, $p \leqslant .03$).

2.6.2. Contextual information: effect of the sound

Emitting a sound at the onset of the movement strongly affected the delays at which the responses varied ($F(1,18) = 9.41$, $p = .006$; ${}_p\eta^2 = 0.34$). Delays were shorter for both full control (mean and SE of the within-participant difference between sound and no-sound in the active condition: 40 ± 35 ms) and no control responses (45 ± 35 ms; see Fig. 4). The sound equally

Table 1
Means and standard errors for the delays at the inflexion point of the fitting curves for full control and no-control in all conditions (the inflexion point of the no-control curve corresponds to the upper limit for the report of partial control).

	Active full-control (ms)	Active no-control (ms)	Passive full-control (ms)	Passive no-control (ms)
Study 1				
No Sound	334.13 ± 26.96	707.76 ± 41.82	291.68 ± 36.52	627.52 ± 41.81
Sound	293.81 ± 35.70	663.03 ± 24. 31	250.39 ± 27.70	646.80 ± 50.08
Study 2				
Low-contingency	295.56 ± 48.47	908.81 ± 64.23	209.04 ± 43.65	845.56 ± 65.99
High-contingency	276.40 ± 47.91	985.51 ± 90.02	201.90 ± 31.90	840.35 ± 63.64

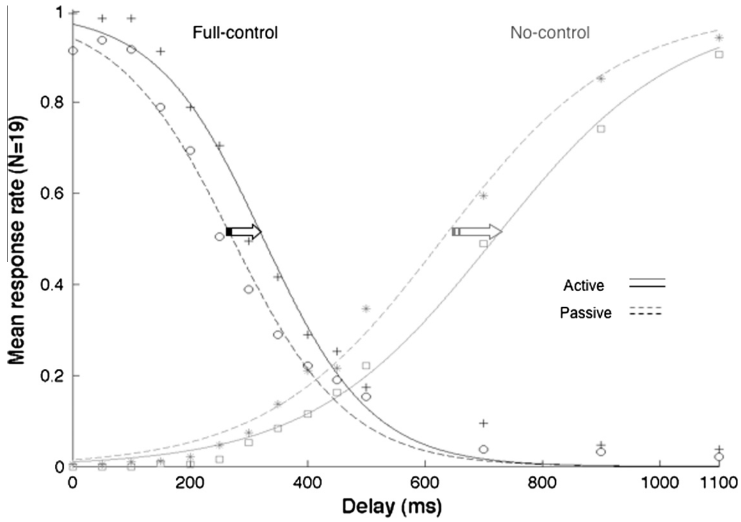

Fig. 3. Mean response rates ($N = 19$) for full control (black) and no-control (grey) responses as a function of the delay (ms) in the active (solid curves) and passive (dotted curves) tasks for the no-sound session. The arrows show the increased delays in the active task when participants shifted from a full sense of control to a partial sense of control (black arrow) and from a partial sense of control to no-control (grey arrow).

shortened the delays in the active and the passive tasks (sound × task, $p > .05$) and for both types of responses (sound × response, $p > .05$); see Fig. 4 and Table 1.

2.6.3. Slopes of the tangents at the inflexion points

We analysed the slopes of the tangent at the inflexion point of the sigmoid curves, which reflect participants' uncertainty in their responses variations. Wilcoxon analyses of the tangents revealed steeper slopes in the active task compared to the passive task for full-control only ($T(19) = 18.00$, $p = .002$) revealing that participants' uncertainty in varying from a full sense of control to a partial sense of control was higher in the passive task. There was no difference of slope between no-sound and sound sessions for either the active or the passive task, showing that the uncertainty in varying from one response to another was not affected by the sound (see Table 2).

3. Study 2: premotor information and prior information

3.1. Participants

Sixteen naive and new participants (mean age 22.88, SD = 4.06) participated in study 2. They were right handed as assessed by the Edinburgh inventory (Oldfield, 1971) and were paid 10 euros for their participation.

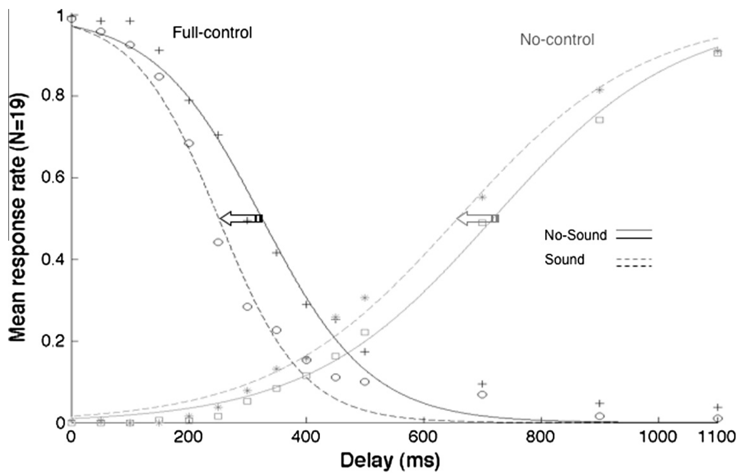

Fig. 4. Mean response rates ($N = 19$) for full control (black) and no-control (grey) responses as a function of the delay (ms) in the active tasks for the no-sound (solid curves) and the sound session (dotted curves).

Table 2
Means and standard errors for the slopes of the tangents at the inflexion points for full control and no-control in all conditions, expressed as response rate/ms.

	Active full-control	Active no-control	Passive full-control	Passive no-control
Study 1				
No Sound	−0.0057 ± 0.001	0.0033 ± 0.0007	−0.0042 ± 0.0005	0.0045 ± 0.001
Sound	−0.0058 ± 0.0006	0.0036 ± 0.0004	−0.0045 ± 0.0005	0.0032 ± 0.0003
Study 2				
Low-contingency	−0.11 ± 0.1	0.0019 ± 0.0002	−0.006 ± 0.0009	0.0032 ± 0.0007
High-contingency	−0.0047 ± 0.0009	0.002 ± 0.0003	−0.01 ± 0.003	0.0022 ± 0.0003

3.2. Materials and methods

We used the same apparatus and material as in study 1. Participants were required to perform two experiments each involving the active and passive tasks. The two experiments differed in the degree of contingency between the participant's movement and its subsequent effect. To control for the degree of contingency in each task there were four conditions. In one condition (condition 1) both action and effect were present: the participant's movement was followed by a ball appearing at the centre of the screen with a variable delay (0; 100; 200; 300; 400; 500; 600; 700; 800; 900 and 1200 ms). In condition 2, the action was present but the effect was absent: the participants' movement was not followed by the appearance of the ball. Finally, for the remaining trials no movement was performed and the ball would either appear (condition 3) or not (condition 4). To obtain these two last types of trials in the active task, participants were thus required to choose on each trial whether to press the button or not. They were told to press the button or not to press it an equal number of times. In the condition in which both the action and the effect were present, participants were required to choose one of three possible responses: 'full-control', 'partial control' or 'no-control' (see Fig. 1, study 2). On the remaining trials, they had to randomly press any button. The contingency values were taken from the study by Moore et al. (2009). The no-contingency ($\Delta p = 0$) and contingency ($\Delta p = 0.5$) blocks only differed with respect to the probabilities of conditions in which the action was absent. Therefore in the no-contingency block of the active and passive tasks the probabilities for conditions 1, 2, 3 and 4 were 0.75; 0.25; 0.75 and 0.25 respectively. In other words, the ball appeared 75% of the time when subjects pressed the button and also 75% of the time when they decided not to press the button. In the high contingency block of the active and passive tasks, the probabilities for conditions 1, 2, 3 and 4 were 0.75; 0.25; 0.25 and 0.75, respectively. In other words, the ball still appeared 75% of the time when subjects pressed the button, but this time it appeared only 25% of the time when they decided not to press the button, therefore strengthening the relationship between button press and the apparition of the ball on the screen. For each task (passive and active tasks, performed in different blocks like in study 1) participants completed one no-contingency and one contingency block of 294 trials each. The two active or passive blocks were always completed one after the other but in a different order across participants. The entire experiment lasted 3 h and participants were free to pause between each of the 25 min blocks.

A training session prior to each task consisted of 10 trials of each condition, with the condition 1 trials having a delay of either 0 ms or 1100 ms.

3.3. Data analyses

We used the same procedure as in study 1 to analyse whether the degree of contingency between an action and its effect affects the delays at which responses varied. However, the rates of full control and no-control responses as a function of delay were only calculated from the trials of condition 1 since participants gave a response about their sense of agency only in this condition. As for study 1, only fits with $R^2 \geqslant 0.70$ were included in the analyses (we had to exclude the data of five participants). The delays at the inflexion points were compared across responses (full control and no-control), tasks (active vs. passive) and sessions (no-contingency vs. high degree of contingency) using a $2 \times 2 \times 2$ repeated measures ANOVA. Post-hoc analyses were conducted using Fisher's LSD and further checked with Wilcoxon tests for pairwise comparisons. We used partial eta squared (${}_p\eta^2$) as our measure of effect size and $p < .05$ was taken as the criterion for significance.

3.4. Results and discussion

We replicated the results of the first study showing an effect of the delay on participants' responses, which varied from full control to partial control and to no-control as the delay increased (Response, $F(1,10) = 130.57$; $p < .0001$; ${}_p\eta^2 = 0.93$). We also replicated the task effect revealing longer delays at which the responses varied in the active task compared to the passive task (Task, $F(1,10) = 6.44$; $p = .03$; ${}_p\eta^2 = 0.39$). Longer delays in the active task were equally observed for both full control and no-control responses as showed by the non-significant interaction between task and response factors. LSD tests confirmed longer delays in the active condition for both full control and no control responses (all LSD tests: $p \leqslant .008$).

Manipulating the degree of contingency between the participant's movement and the ball had no significant impact on the delays at which the responses varied (degree of contingency $F(1,10) = 0.31$; $p = .59$; ${}_p\eta^2 = 0.03$), for any type of response (response $\times$ degree of contingency $F(1,10) = 2.18$; $p = .17$; ${}_p\eta^2 = 0.18$) or any type of task (degree of contingency $\times$ task, $F(1,10) = 0.53$; $p = .49$; ${}_p\eta^2 = 0.05$), (see Table 1) .

The analyses of the slopes of the tangents at the inflexion point of the sigmoid curves did not reveal any significant differences between tasks and between the two contingency sessions (all tests of Wilcoxon $p > .05$) showing that participants' uncertainty in varying from one type of response to another was not significantly different across sessions and tasks (see Table 2).

4. General discussion

The goal of the present study was to assess whether the sense of agency emerges from the integration of internal and external agency cues over time. According to the causal perception model, the sense of agency results from a temporal grouping between an action and its effect. This model suggests that the integration of the action and the effect over time depends on the types of internal agency cues to which the effect will be combined. Manipulating the internal signals (absence or presence of premotor signals) indeed resulted in differences in the delays at which agency judgments shifted (from a full control to a partial control and from a partial control to a no-control). We then showed that additional external contextual signals also affected these delays. These results favour a model of integration of internal agency cues and external agency cues over time.

The importance of temporal contiguity between an action and its effect on the sense of agency over that effect is well known: perturbing this contiguity by delaying the effect leads to a decreased sense of agency over the effect (Farrer et al., 2003b; Leube et al., 2003; Sato & Yasuda, 2005; Shanks & Dickinson, 1987, 1991; Shanks et al., 1989). We characterised further this decreased sense of agency as a function of the delay by specifying the delays at which the sense of agency shifted (from full control to partial control and from partial control to no-control). Participants had a full sense of agency over the effect for delays inferior to 334 ms; a partial sense of agency for intermediate delays between 334 ms and 707 ms and a loss of the sense of agency for delays beyond 707 ms (values computed across subjects in the no-sound session). Partial sense of agency was the preferred choice for intermediate delays consistently across subjects, making unlikely that subjects reported some "partial control" responses only to comply with task demands. Rather, we confirm that a "partial sense of agency" has to be considered as a phenomenologically relevant category and that the sense of agency seems better characterised as a gradual experience (Farrer et al., 2003b, 2008).

The variations in agency judgments might be accounted for by the delay affecting the integration of the action and the effect over time. There is evidence that the sense of agency depends on processes of temporal grouping between an action and an effect (Kawabe et al., 2013). The findings that the delays at which the sense of agency shifted were affected by the internal agency cues available (presence or absence of premotor signals) give support to a sense of agency based on the integration of the action and the effect over time. When premotor signals were available to the participants (in the active conditions), the delays at which agency experiences shifted were increased compared to the passive conditions, suggesting that premotor signals might have induced an extension of the time window within which the effect can be combined with the action. This finding is coherent with a previous study showing a reinforced sense of agency with premotor signals (Sato, 2009). This reinforcing effect could be explained by the higher reliability of premotor signals compared to other agency cues (Sato, 2009), resulting in these signals to contribute with a higher weight to the sense of agency (Synofzik, Vosgerau, & Lindner, 2009; Synofzik, Vosgerau, & Voss, 2013). The present findings further suggest that the higher reliability of premotor signals could also lead to an extension of the time windows of integration; perhaps because these high-reliability signals are maintained available longer for the integration with the effect, resulting in participants having a sense of agency (full or partial) over an extended period of time. This result, however, does not fit well with the results of the study by Shimada et al. (2010), in which there was no difference between active and passive tasks for the delay at which participants perceived a distortion of their own movements. However, the task employed by Shimada et al. (2010) was very different from the present one, since participants were involved in a self-body recognition task requiring them to detect a visual feedback delay between their actual hand movement and an observed virtual hand movement. In the present study, participants were required to judge their sense of control over an effect by choosing one of three choices. The task used by Shimada et al. (2010) therefore did not target the processes by which an action and an effect are perceived as causally related

It could be argued that the differences between active and passive tasks solely reflect differences in the conscious perception of one's own movement because of differences in the strength of proprioceptive signals (Jones, Wessberg, & Vallbo, 2001) and the presence of premotor signals associated with active movements. For example, the phenomenon termed intentional binding, in which the onsets of an action and of its effect are consciously perceived as closer in time than they are in reality, only occurs in situations in which a self-generated movement produces a sensory effect, but not when passive movements lead to the same effects (Haggard, Clark, & Kalogeras, 2002). Therefore, if judging the causal relationship between an action and its effect relies somehow on the conscious perception of their respective onsets, one could argue that difference in the delays between active and passive movements observed in the present study might be explained by intentional binding affecting the causal judgment in the active task but not in the passive task. However, our differences between active and passive conditions can hardly been explained by some differences in timing judgments. First, Nolden, Haering, and Kiesel (2012) have compared the perceived duration between an action and an effect in an active and a passive condition. They showed that intentional binding (shorter perceived duration between an action and an effect) only occurred for longer delays (600 ms) but not for shorter delays (250 ms), suggesting that premotor signals impact the perceived duration only at longer delays. However, in our two experiments we found an impact of premotor signals for our two agency judgments, which corresponded to long (700 ms) and short delays (330 ms). Second, several studies have shown that the predictability of the effect onset is necessary for the binding effect to occur (Cravo, Claessens, & Baldo, 2011; Haggard et al., 2002). Yet, in the present study, the apparition time of the ball could not be predicted because the delays were randomised between trials. For these two reasons, it is unlikely that the extended time window with premotor signals can be explained by intentional binding. Likewise, alternative explanations in terms of differences in the perception of movement could be that the perception of the onset of a movement is noisier when it is voluntarily performed; this would result in greater uncertainty for the active task. However, comparing the slopes of the tangents at the inflexion points, which reflect uncertainty in the variations of the sense of agency we found that uncertainty in varying from one type of response to another was either similar for the active and passive tasks, or if anything was lower in the active task (study 1). Thus, the differences in the delays cannot be explained in terms of differences in the conscious perception of active and passive movements.

Further evidence in favour of a time window of integration is given by the impact of additional contextual information on the delays at which the sense of agency varied. Consistent with previous evidence showing that the context plays a role in the sense of agency (Aarts et al., 2005; Linser & Goschke, 2007; Sato, 2009; Sato & Yasuda, 2005; Wegner & Wheatley, 1999; Wegner et al., 2004), we found that emitting a sound, which was coherent with the subsequent action-effect, at the onset of the movement affected the sense of agency. Specifically, the presence of the sound shortened the delays at which the sense of agency varied. This shortening was observed for both full control and partial control responses and for both active and passive movements. Shorter delays for full control could be due to the delay being better detected with the sound, because of some crossmodal cuing effect in which the sound affects the visual processing of the ball (see Driver & Spence, 2004 for a review). However, the finding that the sound also affected no-control delays goes against a cuing explanation. The effect of the sound on the delay for no-control reports was measured around 660 ms. Yet it is known that the crossmodal cuing effect (a sound affects the processing of a consequent visual cue) does not persist for such long delays. In their theoretical article, Colonius and Diederich (2012) show that the time window for crossmodal response enhancement is inferior to 300 ms. These findings therefore show that the sound directly affected participants' sense of agency, but in a direction opposite to premotor information since it shortened the time window.

The sense of agency is also affected by prior information, like the degree of contingency between an action and an effect that somehow reflects the extent to which the action and the effect co-occur (Moore et al., 2009; Shanks & Dickinson, 1991). In the present study, manipulating the degree of contingency between the movement and its effect had no significant impact on the delays at which the sense of agency varied. This finding is however not inconsistent with the findings of Moore et al. (2009), who showed that the degree of contingency affected the intentional binding between an action and its effect, because our results cannot be interpreted in terms of intentional binding. We therefore show that prior information did not affect the time windows of agency judgements, perhaps because of the very specific temporal properties of prior information. Because prior information is acquired from previous experiences of actions and their effects, it is carried by signals that are not time-locked to action onset; as a consequence it might not be integrated with internal agency cues.

Our findings can be confronted to an influential model (Feinberg, 1978; Frith, 2005; Frith et al., 2000), which proposes that the sense of agency depends on a comparison between the predicted sensory signals that are generated by the internal models of action and the actual sensory signals related to the execution of the action. The comparison between these signals generates an error whose magnitude modulates the intensity of the sense of agency: the lower the error the greater the feeling of having control (Blakemore, Frith, & Wolpert, 1999; Farrer et al., 2008; Knoblich & Kircher, 2004; Leube et al., 2003; Sato & Yasuda, 2005). This model makes predictions about the intensity of the feeling of agency, which depends on the magnitude of the computed error. Here we assessed the time window of agency judgments, not their intensity. We therefore propose that while the intensity of the feeling of agency may depend on a comparison process, the temporal constraints that apply to actions and effects for a sense of agency over an effect to emerge, are best modelled in terms of a time window within which the effect is integrated with the action.

Our present findings also provide new information important for two other current and powerful theoretical proposals about the integration of various agency cues. According to one approach, the sense of agency emerges from the optimal combination of various agency cues with the strengths of these cues being determined by their reliability (Moore et al., 2009; Synofzik, Vosgerau, & Lindner, 2009). According to a second approach, the optimal combination might follow a Bayesian rule with priors generating predictions that constrain the subsequent processing of other agency cues (Fletcher & Frith, 2009; Moore & Fletcher, 2012). However, these proposals do not include any information about the temporal properties of this combination. We therefore complete these ideas by proposing that the sense of agency also depends on a time window within which internal and external agency cues are integrated, and that only external agency cues that are time-locked to action onset are integrated with internal agency cues. This proposal is somewhat similar to the idea recently proposed by Synofzik et al. (2013) of an integration of both internal and external cues.

These findings also speak convincingly in favour of another model of the sense of agency that postulates different levels of integration of agency cues (Synofzik et al., 2008). We may complete this model by further proposing at least two distinct processes that apply to signals that differ in their temporal properties: one process is characterised by a time window of integration that applies to agency cues that are time-locked to the onset of action; another process is characterised by the combination of prior information outside this time window.

Finally, the present findings enable formulating interesting predictions about abnormal agency experiences associated with Schizophrenia and specifically with delusion of influence. Imprecise predicted sensory signals, resulting from a deficit in the internal model of action, have been evoked for explaining the delusion of influence. Imprecise premotor signals might prevent an extension of the time window of integration; this would result in a diminished sense of agency (as is observed in these patients).

5. Conclusion

Our results may clarify the mechanisms by which time plays a role in the sense of agency. We show that action-related signals and effect-related signal have to be integrated within a time window in order for a sense of agency over an effect to emerge and that different agency judgments (full –control and partial control) occurred within distinct time windows. We also show that premotor signals induce a temporal extension of these windows, resulting in having a sense of agency over an extended period of time. Finally, we show that, depending on their temporal properties, additional external agency cues can also be combined with internal agency cues. While contextual signals shorten the time windows of agency, prior information - here the degree of contingency between an action and its effect - donot affect the time windows.

Acknowledgments

We thank Maxime Rosito for technical support; Pierre Baraduc, Pascal Barone, Lionel Nowak and Elisabeth Pacherie for their comments on the results and Karen Reilly for her help in proofreading the final draft. We also thank the anonymous reviewers for their thorough review of this manuscript.

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