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Sense of control depends on fluency of action selection, not motor performance

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ABSTRACT

Sense of agency refers to the feeling of controlling one's own actions, and, through these actions, events in the outside world. Sense of agency is widely held to involve a retrospective inference based on matching actual effects of an action with its expected effects. We hypothesise a second, prospective aspect of sense of agency, reflecting the *fluency of action selection*, based on results from subliminal priming of actions. When people responded to a target that was compatible with a preceding subliminal prime, they felt stronger sense of control over a subsequent colour effect than when the preceding prime was incompatible. Importantly, compatible and incompatible primes had the same predictive statistical relation to the colour effect. We next investigated whether differences in sense of control could be based on monitoring motor performance. By varying the timings of mask and target, we compared sense of control between a Positive Compatibility condition, where compatible primes facilitated performance, and a Negative Compatibility condition, where compatible primes impaired performance. We found that compatible priming again enhanced sense of control, irrespective of its effects on performance. We present a simple model of the prospective aspect of sense of agency, in which early signals reflecting action selection processing make a direct, experiential contribution to sense of control. Sense of agency may be partly based on an experience-based 'feeling of doing', analogous to the metacognitive 'feeling of knowing'.

1. Introduction

Sense of agency refers to the feeling of controlling one's own actions, and, through these actions, events in the outside world. Previous research suggested that this subjective feeling of control depends strongly on predicting outcomes: sense of agency gets stronger as the match between predicted and actual action outcomes gets closer (Blakemore, Wolpert, & Frith, 1998; Farrer et al., 2008; Linser & Goschke, 2007; Moore & Haggard, 2008; Sato & Yasuda, 2005; Wegner & Wheatley, 1999). For example, if I intend to turn on the light by pressing a switch, and the light comes on after I press the switch, then I am likely to feel that *I* caused the light to come on. On this view, the basic computation underlying sense of agency involves matching the intended effects of action against its actual effects (Farrer et al., 2003; Farrer & Frith, 2002). Interestingly, this computation can only be performed *retrospectively*, after information about outcomes becomes available, even though the intention to achieve a given outcome includes a future-directed component (Pacherie, 2000, 2008). For example, people may monitor whether their actions produce the effects they expected, and thus metacognitively infer whether they caused those effects or not (Miele, Wager, Mitchell, & Metcalfe, 2011).

An alternative possibility, that sense of agency is partly generated *prospectively*, in advance of knowing the actual outcome of actions, has however received recent support

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(Nahab et al., 2011; Wenke, Fleming, & Haggard, 2010). On this view, selecting between alternative possible actions might itself generate a sense of agency. For example, faced with two electrical switches, if I deliberately choose the lighting switch rather than the heating switch, I may experience a stronger sense of control than if I hesitate in confusion over which switch to choose. Importantly, this difference in subjective experience of agency precedes action and outcome, and is independent of them. In both cases described above, I might actually press the lighting switch, and make the lights come on. Thus, monitoring signals generated at the point of *action selection* could contribute to a sense of agency, independently of objective facts of action execution and outcome.

In a recent study, Wenke et al. (2010) investigated this prospective component of control using an experimental design that dissociated the processes of action selection from action–outcome matching. They used subliminal priming to manipulate fluency of selection between left and right keypresses in response to suprathreshold left- and right-pointing arrow targets. Subliminal prime arrow directions were either identical (compatible condition) or opposite (incompatible condition) to the subsequent target direction. Each keypress was followed by a colour patch. One set of colours was shown when prime and target were compatible, and another set when prime and target were incompatible. Participants reported a stronger sense of control over the colour patch when they acted compatibly with a prime that they could not even see, relative to incompatibly. Importantly, this effect was not due to predictability of action outcomes, since the relation between keypress action and colour outcome was always equally predictable. Rather, the stronger experience of control when prime and target were compatible could only be explained by the *fluency* of action selection – i.e., by an internal signal influenced by the prime–target relation. Crucially, this fluency-related signal must have been generated at the action selection stage and sampled *before* the action was executed (Wenke et al., 2010). Further, these primes were subliminal. Therefore, the changes that they caused in sense of control were unlikely to involve conscious metacognitive inference (Miele et al., 2011). Rather, compatible primes might have generated an experience-based form of metacognition: a ‘feeling of doing’ analogous to the well-studied ‘feeling of knowing’ (Koriat, 2000; Muñoz, 2011).

However, the results are also compatible with a very different interpretation, which has no need for monitoring of internal fluency signals. Specifically, participants might perceive control based on monitoring of their own motor performance, for example their response times (RTs). Since RTs are lower on compatibly- than incompatibly-primed trials (Dehaene et al., 1998; Schlaghecken & Eimer, 2000; Schlaghecken, Rowley, Sembi, Simmons, & Whitcomb, 2007), participants would therefore feel more control on compatible trials, because they respond more rapidly. On this second view, agency would depend on *retrospective* monitoring of action execution performance (Corallo, Sackur, Dehaene, & Sigman, 2008; Marti, Sackur, Sigman, & Dehaene, 2010), not on *prospective* monitoring of premotor fluency signals.

To distinguish between these two accounts of sense of control, we used an experimental procedure that dissociated fluency of action selection from RT monitoring. Specifically, we increased the interval between mask and target (see Fig. 1) to take advantage of a Negative Compatibility Effect (NCE) in priming. The NCE occurs only at longer mask–target intervals, and is generally interpreted as an automatic inhibition of an initially-primed response (Eimer & Schlaghecken, 1998, 2003; Klapp & Haas, 2005; Lingnau & Vorberg, 2005; Schlaghecken & Eimer, 2002, 2006; Sumner & Husain, 2008; but see Jaśkowski (2008) for an alternative account of this auto-inhibition process). If a prime-induced activation is not rapidly confirmed by a target, then an auto-inhibitory process is thought to suppress response activation below baseline, since the primed action is now shown to be inappropriate (see Fig. 6a, upper panel). Importantly, the locus of the NCE therefore lies after the action selection stage.

Thus, compatible priming accelerates RTs at short mask–target latencies, (PCE), but paradoxically *increases* RTs at longer latencies (NCE). By combining this factor with our previous design for assessing sense of control, we could directly distinguish between performance monitoring and action selection accounts. A stronger experience of control on compatible trials, *despite slower response times generated at NCE latencies*, would provide strong evidence for a prospective contribution of action-selection fluency to sense of control. Alternatively, a stronger experience of control for faster responses, irrespective of prime compatibility, would provide evidence that sense of agency depends on performance monitoring. We tested these two predictions in Experiment 1. In Experiment 2, we replicated our findings in a new sample of participants, additionally including trials with neutral primes. We also formally tested whether participants were conscious of the direction of primes stimuli.

2. Experiment 1

2.1. Material and methods

2.1.1. Participants

Eighteen participants (8 females and 10 males aged 21–34 years), with normal or corrected-to-normal vision, were recruited to participate in the study. They provided written informed consent prior to the experiment and were paid €10 for their participation. The experiment was approved by the UCL Research Ethics Committee.

2.1.2. Apparatus and materials

The visual display was presented on a computer screen placed at about 60 cm from the participant (display mode = $800 \times 600 \times 32$, 60 Hz). The experiment was programmed and stimulations were delivered using Presentation (Neurobehavioral Systems, Albany, California, http://www.neurobs.com).

Primes consisted of grey left- or right-pointing arrows followed by isoluminant metacontrast masks constructed by superimposing left- and right-oriented primes (Fig. 1). The outer shape of the mask was rectangular. The targets

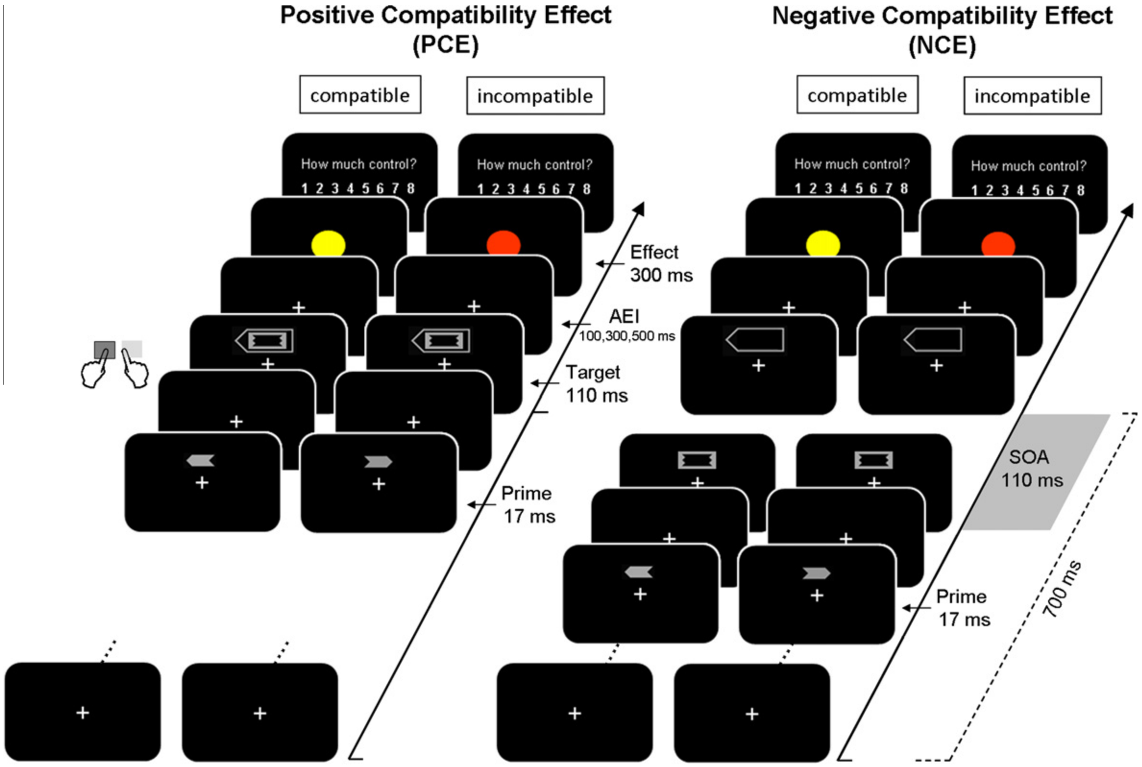

Fig. 1. Experiment 1: Schematic of trial procedure and stimuli. Example trials from the four possible combinations of prime–action compatibility and PCE/NCE. Participants were instructed to respond to the target stimuli, and were not informed of the presence of the primes. Primes and masks could appear randomly above or below fixation on each trial. On PCE trials, the mask–target Stimulus Onset Asynchrony (SOA) was 0, with the mask appearing within the inner cutout of the target. On NCE trials, the mask–target SOA was 110 ms, with the target being presented immediately after the mask disappeared. Participants were asked to estimate how much control they felt they had over the colour patch that appeared 100, 300, or 500 ms, after their response. AEI: Action-effect interval.

were supraliminal arrows that unambiguously pointed to left or right, with a cutout large enough for the mask to fit without touching the inner contours of the target (Lingnau & Vorberg, 2005). Prime and mask stimuli could appear randomly above or below fixation to enhance the masking effect (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). Action outcomes were circular colour patches of red, green, blue, or yellow. All stimuli appeared on a grey background.

2.1.3. Design and procedure

The task was to respond to the direction of the target arrow by pressing the corresponding response button with the right or left index finger.

Examples of each (left and right) target were presented during experimental instruction so that participants would become acquainted with the target stimuli. No reference was made to the existence or appearance of the primes.

On half of the trials in each block at random, the prime and the target (and therefore also the manual response) were *compatible*, while on the remaining trials they were *incompatible* (see Fig. 1). In addition, trials were randomly divided into PCE and NCE trials, by inserting (NCE) or omitting (PCE) a 110 ms delay between mask and target (Lingnau & Vorberg, 2005).

Action effects consisted of coloured circles that appeared on the screen 100, 300 or 500 ms after the response to the target. This jitter in action-effect delay was introduced because delay strongly influences sense of control (Haggard, Clark, & Kalogeras, 2002; Wenke et al., 2010), and was therefore expected to increase the range of participants' control ratings. Red, green, blue, or yellow colour patches were presented, according to whether the trial was prime–target compatible or prime–target incompatible. In each block, two colours (one for each hand) were assigned to prime-compatible responses, another two colours to prime-incompatible responses. Colours were rotated via a Latin square such that, across all four blocks, each colour appeared in each compatibility condition for each hand. After the colour patch was displayed, participants judged how much control they felt they had over the colour effect by using a scale ranging from 1 (no control) to 8 (complete control).

When making their judgment, participants were explicitly given the instruction to judge the extent to which they thought they had controlled the appearance of the coloured patch through their action. The control judgement therefore concerned the causal relationship between the action and the consequent effect, rather than simply the effect, or simply the action alone. Such control judgements are a standard way of assessing retrospective agency while avoiding contamination by 'self-other' discrimination processes that are more relevant to "ownership" rather than to agency (see Synofzik, Vosgerau, and Newen (2008) for a review). Subjects were not told that they had in fact no real control over the appearance of the colour effect.

2.1.4. Timeline

Each trial began with a central fixation cross which remained visible until the colour-effect stimulus appeared. The prime was presented for 17 ms, followed by a mask after an SOA (Stimulus Onset Asynchrony) of 33 ms. Mask and target durations were both 110 ms. These parameters were chosen because extensive previous studies showed that conscious perception of prime direction is impossible with these exposures (see Lingnau & Vorberg, 2005; Vorberg et al., 2003). In particular, the prime–mask asynchrony strongly influences prime visibility. Vorberg et al. (2003) found that participants could not report the identity of the primes at prime–mask SOAs from 14 to 70 ms, even after extended practice of more than 3000 trials.

Mask–target SOA was varied in order to induce either a PCE or a NCE, following the same procedure as in Lingnau and Vorberg (2005). On PCE trials, the mask–target SOA was 0, with the mask appearing within the inner cutout of the target. On NCE trials, the mask–target SOA was of 110 ms, with the target being presented immediately after the mask disappeared. Note that trial events were timed so that the target stimulus always appeared 700 ms after the fixation cross, irrespective of the PCE/NCE manipulation (see Fig. 1).

The response window was set to 1200 ms. If participants failed to respond within this time window, or made an incorrect response, they saw a black X instead of a coloured circle. The coloured patches representing action effects remained on the screen for 300 ms. After a jittered delay (grey background) varying from 1 to 2 s, a rating scale appeared for 1500 ms, allowing the participant to judge the level of control she felt over the colour patch. Once the participant made her control judgment, the rating scale was replaced by a fixation cross until the end of the 1500 ms response window.

The experiment consisted of four blocks of 64 trials each. When an error occurred, the corresponding trial was repeated at the end of each block (up to 10 error trials per block), ensuring that all colours were seen equally often despite any errors.

2.1.5. Data analyses

Error rates (ERs), response times (RTs) were analysed independently using 2 × 2 repeated-measures ANOVAs with prime–target compatibility (compatible vs. incompatible) and mask–target SOA (PCE vs. NCE) as within-subjects factors. Control ratings for colour effects were analysed using a 2 × 2 × 3 repeated-measures ANOVA with mask–target SOA, prime–target compatibility, and action-effect interval (100, 300, 500 ms) as within-subjects factors. Post-hoc Fisher tests were used to identify differences between conditions.

2.2. Results

2.2.1. Response times

Our analyses focused on demonstrating PCE and NCE effects. ANOVA showed no main effects of compatibility ($F(1,17) = 0.14$, $p = 0.70$) or mask–target SOA ($F(1,17) = 0.21$, $p = 0.65$). There was a significant interaction between mask–target SOA (i.e., PCE vs. NCE latencies) and prime–target compatibility (compatible vs. incompatible): ($F(1,17) = 12.36$, $p = 0.002$) (Fig. 2, upper panel). As expected, on PCE trials, participants' responses to arrow targets following compatible primes were faster than following incompatible primes (post-hoc Fisher test, $p = 0.013$). Also as expected, NCE trials reversed the

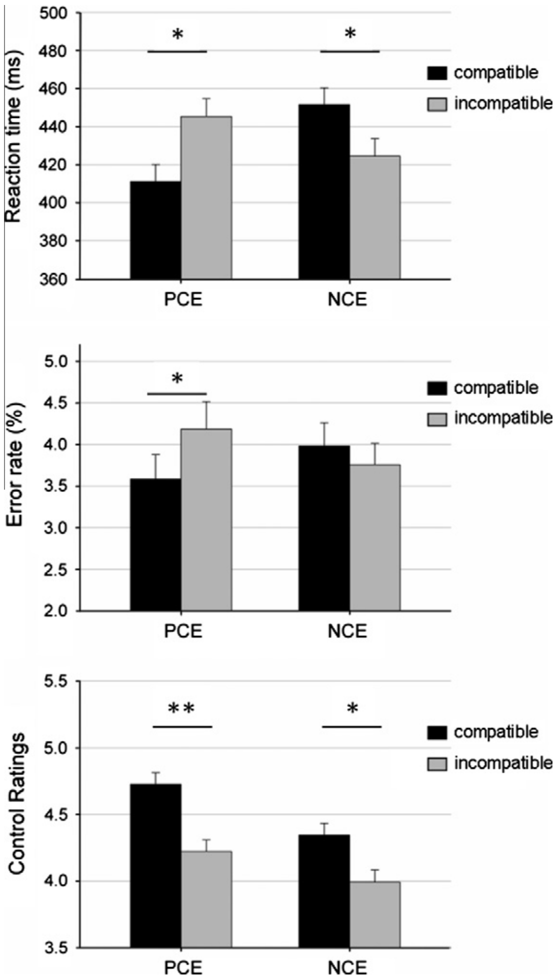

Fig. 2. Experiment 1: Mean response times (ms), mean error rates (%), and mean control ratings, on compatible and incompatible trials, for each mask–target SOA (PCE/NCE). At NCE latencies, the positive compatibility effect (PCE) on performance measures is reversed (response times), or abolished (error rates), so that performance costs now occur on compatible trials and benefits on incompatible trials. However, the relationship between compatibility and sense of control is similar under PCE and NCE conditions: participants felt more in control in compatibly-primed than incompatibly-primed trials, irrespective of how priming affected performance. All error bars indicate SEM. *: $p < .05$; **: $p < .005$.

polarity of this effect, with participants' responses being slower for compatible than for incompatible trials (post-hoc Fisher test, $p = 0.041$) (see also Supplemental material, "Correlation analyses", and Table S2).

2.2.2. Error rates

There was no significant main effects of compatibility ($F(1,17) = 0.56$, $p = 0.46$) or mask–target SOA ($F(1,17) = 0.002$, $p = 0.96$). The interaction effect between mask–target SOA and compatibility was significant ($F(1,17) = 6.34$, $p = 0.022$) (Fig. 2b). On PCE trials, as predicted, participants made more errors in incompatible than in compatible trials (post-hoc Fisher test, $p = 0.019$). On NCE trials, a numerical effect in the opposite direction was found, but did not reach significance (post-hoc Fisher test, $p = 0.34$).

2.2.3. Control ratings

First, we found a main effect of compatibility ($F(1,17) = 6.45$, $p = 0.02$). This replicated the effect reported previously by Wenke et al. (2010), with participants experiencing more control over the colour patch when primed compatibly than when primed incompatibly. There was also a trend towards a main effect of mask–target SOA ($F(1,17) = 3.38$, $p = 0.083$), with PCE trials producing higher control ratings than NCE trials. Importantly, the interaction between SOA and prime–target compatibility was far from significance ($F(1,17) = 0.43$, $p = 0.521$) (Fig. 2, lower panel). For comparability with the RT analysis, we also performed post-hoc tests comparing control ratings between compatible and incompatible trials in PCE ($p = 0.005$) and NCE ($p = 0.03$) conditions. In summary, on *both* PCE and NCE trials, participants experienced higher levels of control over action effects following *compatible* prime–target associations.

In addition, we found a predicted main effect of action-effect interval ($F(1,17) = 46.38$, $p < 0.001$). Post-hoc testing showed that participants experienced strongest sense of control with 100 ms response-effect intervals, less control with 300 ms, and least control with 500 ms (see Supplementary Table S1). All pairwise comparisons were significant ($p < 0.001$). Importantly, there was no significant interaction between action-effect interval and compatibility ($F(1,17) = 0.47$, $p = 0.62$): thus, predictability of the effect did not differently influence sense of control across compatible and incompatible trials. There was a trend for a significant interaction between action-effect interval and SOA ($F(1,17) = 2.74$, $p = 0.08$). The three-way interaction between all the factors was far from significance ($F(1,17) = 0.04$, $p = 0.96$).

3. Experiment 2

3.1. Material and methods

3.1.1. Participants

Twelve participants (6 females and 6 males aged 22–31 years), with normal or corrected-to-normal vision, were recruited to participate in the second experiment. The experiment consisted of two separate, but consecutive, tests: a PCE/NCE test (based on that presented in Experiment 1, but see below), followed by a prime discrimination test. All participants provided written informed consent and were paid €10 for their participation.

3.1.2. PCE/NCE test

3.1.2.1. Apparatus and materials. Apparatus and materials were the same as in Experiment 1, except that neutral primes were also included, together with left- or right-pointing prime arrows. Neutral primes were constructed by superimposing left- and right-oriented primes (Lingnau & Vorberg, 2005) (see Fig. 3).

3.1.2.2. Design and procedure. On one third of the trials in each block at random, the prime and the target were *compatible,* while on the other one third, they were *incompatible*. In the remaining one third of the trials, the primes were *neutral*. As in Experiment 1, trials were randomly divided into PCE and NCE trials, by inserting (NCE) or omitting (PCE) a 110 ms delay between mask and target.

The experiment consisted of six blocks of 54 trials each. When an error occurred, the corresponding trial was repeated at the end of each block (up to 10 error trials per block), ensuring that all colours were seen equally often despite any errors. The timeline in Experiment 2 was exactly the same as in the first experiment.

3.1.2.3. Data analyses. Error rates (ERs) and response times (RTs) were analysed independently using 2×3 repeated-measures ANOVAs with prime–target relation (compatible vs. incompatible vs. neutral) and mask–target SOA (PCE vs. NCE) as within-subjects factors. Control ratings for colour effects were analysed using a $2 \times 3 \times 3$ repeated-measures ANOVA with mask–target SOA, prime–target relation, and action-effect interval (100, 300, 500 ms) as within-subjects factors. Post-hoc Fisher tests were used to identify differences between conditions.

3.1.3. Prime discrimination test

Following the PCE/NCE experiment, each participant additionally performed a direct assessment of prime discriminability. Defining criteria for non-conscious perception is fraught with debate (Erdelyi, 2004). Criteria can be either subjective (based on self-report) or objective (based on forced-choice performance). As our aim in this investigation was to ensure the unconscious nature of our prime stimuli, we selected the more conservative, objective criterion of awareness. Furthermore, to ensure that the prime discrimination test was a valid measure of prime perception during the PCE/NCE experiment, we matched the designs of the prime discrimination and of the control task in as many ways as possible (Schmidt & Vorberg, 2006). Thus, in the prime discrimination task, participants were explicitly informed of the presence of a prime, and asked to identify its direction on each trial (left or right) using a left or right keypress. Other elements of the trial sequence remained identical to the PCE/NCE experiment, except that the colour effect was not presented (effect stimuli in the main experiment were in any case independent of prime direction). To ensure that conscious judgement of the prime direction was not contaminated by the unconscious activation of a motor response, participants were only

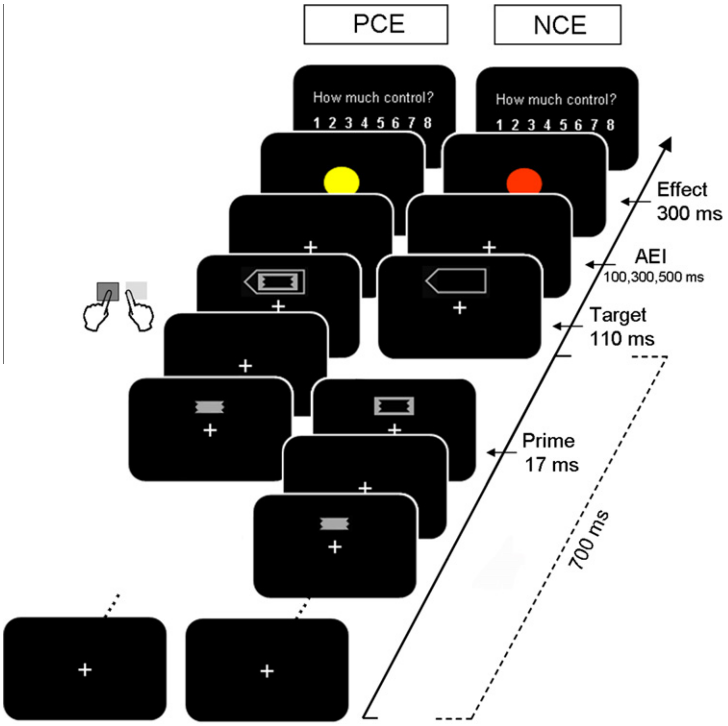

Fig. 3. Experiment 2: Schematic of trial procedure and stimuli. Example trials from the two PCE/NCE conditions with neutral primes. The experimental design also included four other types of trials, as in Experiment 1: compatible and incompatible trials with left- or right-pointing arrow primes, and PCE/NCE conditions (not shown). AEI: Action-effect interval.

permitted to report 600 ms after the mask had appeared (Vorberg et al., 2003). The start of the reporting interval was signalled by a 1000 Hz tone played for 150 ms. The prime discriminability test consisted of two blocks of 54 trials each. Responses to the primes were analysed using signal detection theory (Green & Swets, 1966) allowing us to compute a measure of prime discriminability (d') for each subject and each mask–target SOA condition (PCE/NCE).

3.2. Results

3.2.1. Response times

ANOVA showed no main effects of prime–target relation ($F(2,22) = 0.32$, $p = 0.72$) or mask–target SOA ($F(1,11) = 0.91$, $p = 0.35$). There was a clear trend towards an interaction effect between mask–target SOA (i.e., PCE vs. NCE latencies) and prime–target relation (compatible vs. incompatible vs. neutral) ($F(2,22) = 3.00$, $p = 0.07$) (Fig. 4, upper panel). This interaction followed the pattern of Experiment 1, and was explored further with post-hoc testing. As before, on PCE trials, participants' responses to arrow targets following compatible primes were faster than following incompatible primes (416 ms vs. 454 ms; post-hoc Fisher test: $p = 0.04$). NCE trials again reversed the polarity of this effect, with participants' responses tending to be slower for compatible than for incompatible trials. However, the size of this effect was reduced compared to Experiment 1, and it did not achieve significance (465 ms vs. 441 ms; post-hoc Fisher test, $p = 0.19$). On PCE trials, we found a numerical effect of compatible, relative to neutral, priming, with RTs tending to be faster in compatible trials than neutral trials (414 ms vs. 434 ms), whereas this effect tended to reverse on NCE trials, with responses following neutral trials tending to be faster than responses following compatible trials (438 ms vs. 461 ms). Note that these two numerical effects did however not reach significance (PCE: $p = 0.31$; NCE: $p = 0.16$) (see also Supplemental material, "Correlation analyses", and Table S3).

3.2.2. Error rates

There was no significant main effects of prime–target relation ($F(2,22) = 0.34$, $p = 0.71$) or mask–target SOA ($F(1,11) = 0.66$, $p = 0.43$). The interaction effect between mask–target SOA and prime–target relation was not significant neither ($F(2,22) = 0.92$, $p = 0.41$) (Fig. 4, middle panel). On PCE trials, a numerical effect was found that was consistent with Experiment 1: participants made more errors in incompatible than in compatible (4.63% vs. 3.97%) and neutral trials (4.63% vs. 4.06%). The effect, however, did not reach significance (post-hoc Fisher test, incompatible vs. compatible, $p = 0.17$; incompatible vs. neutral, $p = 0.22$).

3.2.3. Control ratings

Inspection of Fig. 4 shows that the experience of control over action effects was highest following compatible primes, lowest following incompatible primes, and intermediate

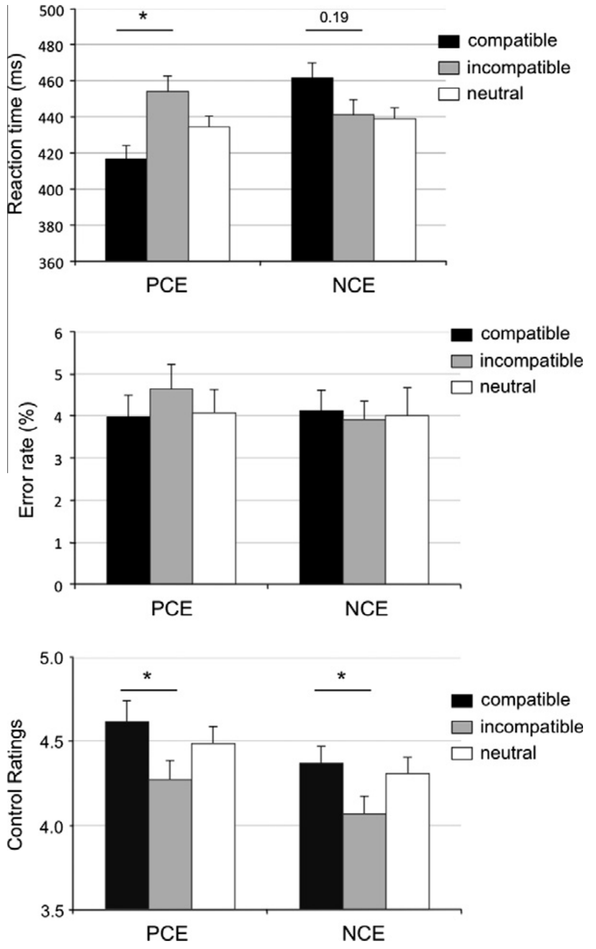

Fig. 4. Experiment 2: Mean response times (ms), mean error rates (%), and mean control ratings, on compatible and incompatible and neutral trials, for each mask–target SOA (PCE/NCE). All error bars indicate SEM. $*$: $p < .05$.

following neutral primes, in both PCE and NCE conditions. ANOVA did not reveal any main effect of prime–target relation ($F(2,22) = 0.66$, $p = 0.52$). There was a trend towards a main effect of mask–target SOA ($F(1,11) = 3.09$, $p = 0.10$), with PCE trials producing higher control ratings than NCE trials. Importantly, the interaction between SOA and prime–target relation was far from significance, as in Experiment 1 ($F(2,22) = 0.06$, $p = 0.93$) (Fig. 4, lower panel). For comparability with the RT analysis, we also performed post-hoc tests comparing control ratings between compatible and incompatible trials for PCE and NCE trials, and found significant differences in both conditions (PCE: $p = 0.014$, NCE $p = 0.029$). We also compared control ratings between neutral and compatible trials in PCE ($p = 0.33$) and NCE ($p = 0.63$) conditions, and between neutral and incompatible trials in PCE ($p = 0.11$) and NCE ($p = 0.076$) trials as well. In summary, on *both* PCE and NCE trials, participants experienced higher levels of control over action effects following *compatible* prime–target associations – consistently with the pattern of ratings found in Experiment 1. Interestingly, compatible priming did not significantly boost sense of control compared to neutral priming. However, participants tended to feel less control when incompatibly vs. neutrally-primed on both PCE and NCE conditions.

In addition, we again found a main effect of action-effect interval ($F(2,22) = 42.55$, $p < 0.001$). Post-hoc testing showed that participants experienced strongest sense of control with 100 ms response-effect intervals, less control with 300 ms, and least control with 500 ms. All pairwise comparisons were significant ($p < 0.001$). Importantly, there was no significant interaction between action-effect interval and prime–target relation ($F(4,44) = 1.49$, $p = 0.22$): as in Experiment 1, predictability of the effect did not differently influence sense of control across compatible and incompatible and neutral trials. The interaction between action-effect interval and SOA was not significant ($F(2,22) = 0.48$, $p = 0.62$) nor was the three-way interaction between all the factors ($F(4,44) = 0.94$, $p = 0.44$).

3.2.4. Prime-discrimination results

Detection analyses confirmed that primes were below the threshold of awareness, with mean d' not significantly different from zero (PCE, mean $d' = 0.037 \pm 0.14$, $p = 0.38$; NCE, mean $d' = -0.043 \pm 0.13$, $p = 0.29$) and no d' greater than two standard deviations above the mean. Note that these results are consistent with d' analyses performed in two previous studies using the same stimuli and procedure (Chambon, Wenke, Fleming, Prinz, & Haggard, 2012; Wenke et al., 2010).

To ensure that even slight individual variations in prime discrimination could not account for variations in participants' sense of control, we also used linear regressions to explore whether individual participants' d' values could be related to their control ratings in compatible and incompatible trials of the PCE/NCE experiment. These analyses did not reveal any significant association, either on compatible (PCE: $R = -0.26$, $p = 0.41$; NCE: $R = -0.38$, $p = 0.21$) or incompatible trials (PCE: $R = 0.06$, $p = 0.84$; NCE: $R = -0.14$, $p = 0.64$) (Fig. 5). Interestingly, the sign of the regression coefficients in fact indicated that participants with better prime discrimination felt *less* sense of control. Therefore, prime discrimination performance seems unlikely to explain why participants feel *more* control in compatible, relative to incompatible, trials.

4. Discussion

Previous evidence suggested that a subjective sense of agency arises when external events occur in close association with an action that people perform, or simply intend to perform (Blakemore et al., 1998; Farrer et al., 2008; Moore & Haggard, 2008; Sato, 2009; Wegner, Sparrow, & Winerman, 2004). Most models conclude from this evidence that agency is inferred *retrospectively*, after an action, on the basis of its external consequences. Our results extend these views in two important ways. First, across two experiments, we showed that sense of agency is *also* informed by early signals generated at the moment of action selection. Importantly, these signals were not related to anticipation of the effects of action, because the

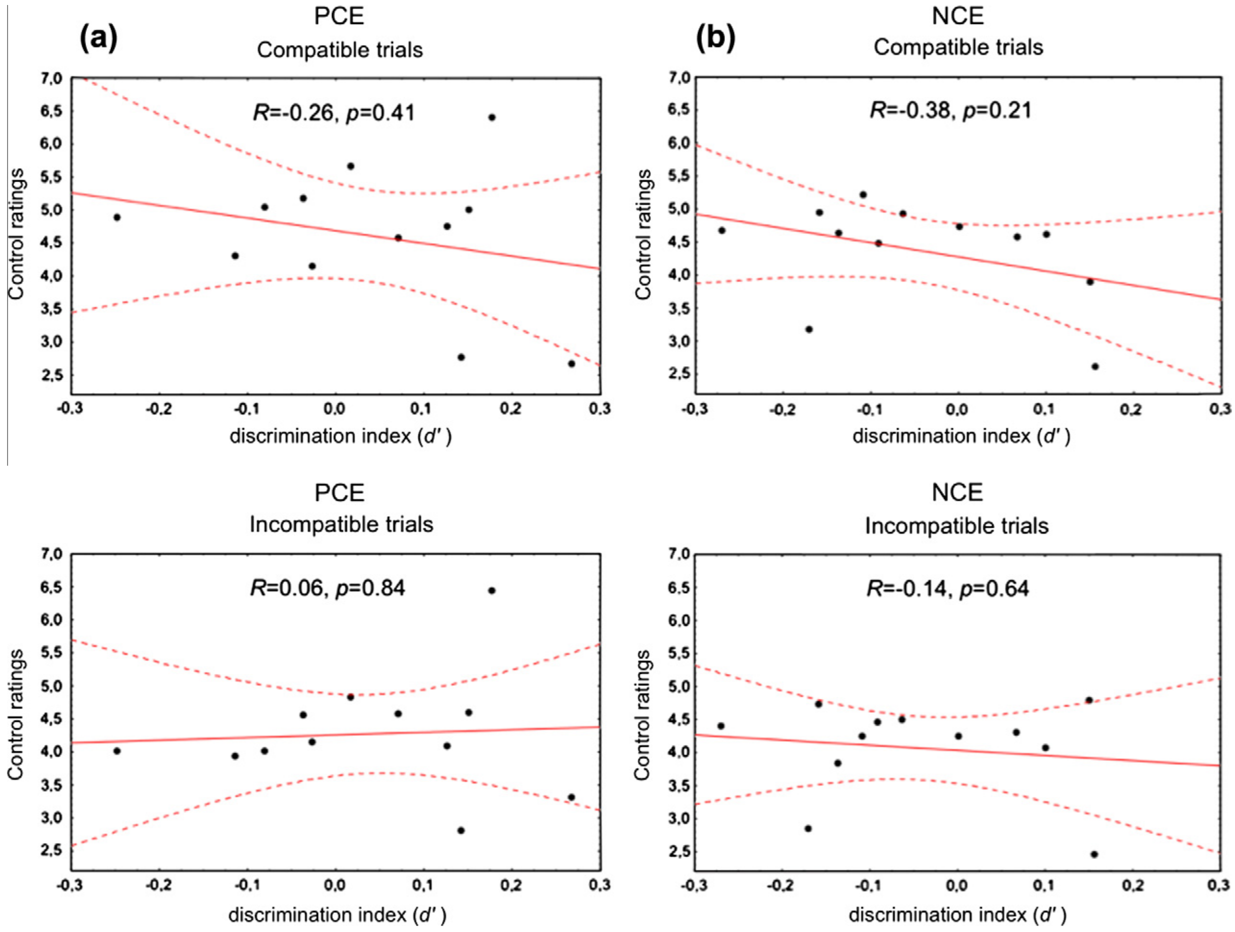

Fig. 5. Regression analyses between prime discrimination performance (d') and control ratings in compatible and incompatible trials of PCE and NCE conditions. The linear regression lines are shown in red. (a) PCE trials; (b) NCE trials. The red dashed line around the regression line represents the 95% confidence interval (CI)." (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

colour-patch action effects in our experiment were equally predictable across compatible and incompatible priming conditions. Specifically, the colour was independent of the *direction* indicated by both the subliminal prime and the target arrow, but depended only on the *compatibility relation* between the prime and the subsequent target. Thus, the stronger experience of control when prime and target were compatible could not be explained by the prime directly predicting the effect. Rather it could only be explained by the *fluency* of action selection processing, as manipulated by our prime–target relation. Thus, sense of control depends on action selection signals generated in advance of the action itself, and before action outcomes are known (see also Wenke et al., 2010). In Experiment 2, we included neutral primes. These produced control ratings intermediate between those for compatible primes and incompatible primes (though not statistically different from either in this small, follow-up experiment). While caution is required in interpreting statistically null results, the intermediate ratings obtained with neutral primes suggests that the prospective component of agency involves both an experienced control benefit for action selection fluency, *and* a control cost for action selection dysfluency. Further, adequately-powered studies might usefully assess which of these influences is stronger.[1]

We further show that effects of action fluency on subjective control are *prospective* – i.e., arise during the processes that select and generate action – and cannot be due to participants *retrospectively* monitoring their own motor performance. We used the NCE effect to reverse the normal relationship between prime–target compatibility and RTs, but found that subjective control remained unaffected, in two separate experiments. Thus, in compatible NCE trials, participants experienced *stronger* control

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[1] The effects reported here could also be interpreted in terms of access to action representations, rather than processing fluency. On this view, compatible primes would increase the «mental accessibility» of the response, through increasing the ease with which the representation of the response can be activated by the target (Eitam & Higgins, 2010). Easier access might then be experienced as greater control over outcomes following that particular response. This explanation is not incompatible with the fluency account, and indeed it is difficult to choose between them on the basis of the present data.

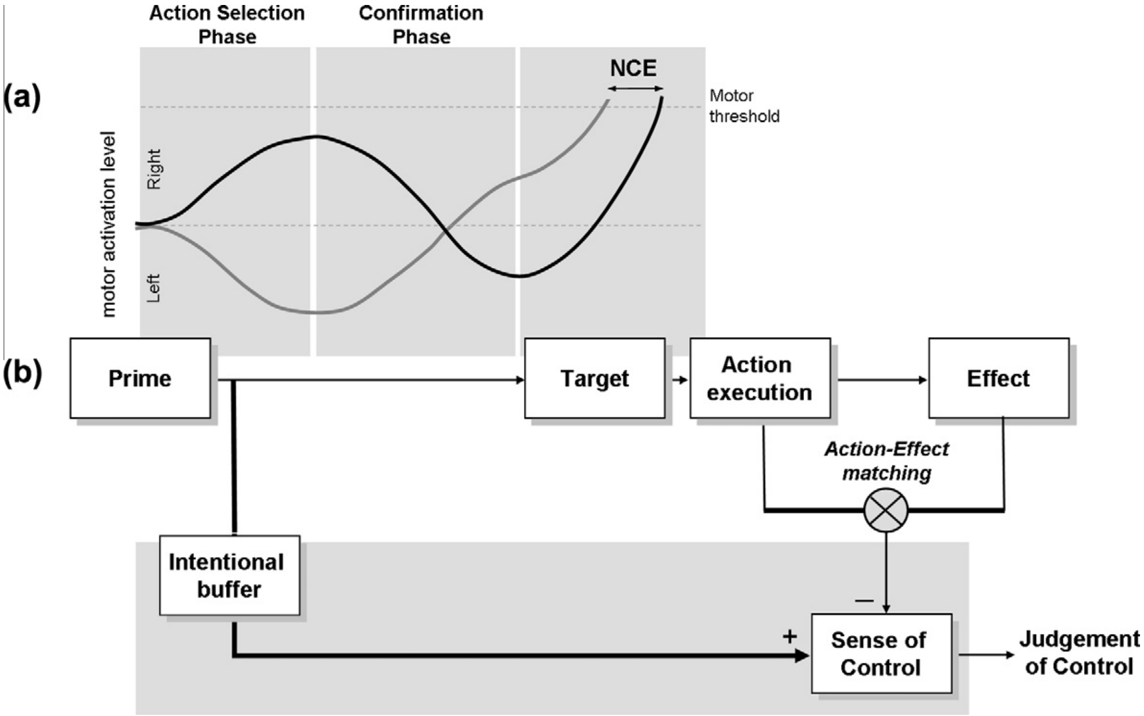

Fig. 6. Dissociating sense of control from performance monitoring. Upper panel (a) time course of sub-threshold response activation following a right-pointing prime that is either compatible (black) or incompatible (grey) with the upcoming target. When no additional evidence – such as a compatible target – confirms the initial prime-induced activation, it is automatically inhibited. This inhibition leads to relative facilitation of the incompatible activation. Thus, when the target occurs, the motor activation threshold can be reached faster than in the compatible case, creating the NCE (adapted from Sumner and Husain (2008)). (b) Two processes contributing to sense of control. Action-effect matching: Control can be retrospectively inferred from comparing the predicted effect of a response with its actual effect using a comparator. The sense of control is inversely related to the comparator output. Lower grey panel: In addition, sense of control depends on an early signal generated during action selection, and temporarily held in an intentional buffer, in advance of the action itself. This signal is positively related to sense of control.

despite *slower* response times and higher error rates, while in incompatible NCE trials they experienced less control despite faster RTs. Although studies using other tasks show that people can monitor RTs to estimate their performance (Corallo et al., 2008; Marti et al., 2010), our results suggest that the prospective aspect of control does not depend on such performance monitoring.

The NCE is normally considered the result of an automatic, inhibitory, mechanism within the brain's action programming centres (Schlaghecken, Bowman, & Eimer, 2006; Schlaghecken & Eimer, 2002, 2006). This auto-inhibition occurs when no additional evidence – such as a congruent target – provides follow-up confirmation of the initial activation elicited by the prime (see Schlaghecken et al. (2007) for a review). Interestingly, this model of premotor processing posits a strict serial order of evidence accumulation, allowing us to localise the prospective signals for sense of control within the processing chain. Clearly, the initial prime-induced activation of motor intentions that causes the PCE must precede the subsequent window of follow-up confirmation that causes the NCE (Schlaghecken et al., 2007) (see Fig. 6a, upper panel). Our data shows that sense of control depends on initial prime-induced activation of motor intentions, but is unaffected by whether follow-up confirmation occurs (as in PCE) or not (as in NCE). Therefore, sense of control must depend on signals generated *before* the stage of the auto-inhibition process thought to underlie the NCE.

Our data also allow a second comment on serial processing underlying the sense of control. We showed that prime–target compatibility and response-effect interval both had strong effects on sense of control, but that these effects were strictly additive, with no convincing interaction between them ($F < 1$). By the additive factors logic (Sternberg, 1969), prime compatibility and response-effect intervals should therefore influence different stages in the processes that generate sense of control. The influence of response-effect intervals must, necessarily, be retrospective, because interval duration is known only once the colour effect terminates the interval. Similarly, the influence of prime compatibility must necessarily be prospective, because prime compatibility was statistically independent of action and colour effect in our design. Thus, while the absence of interaction must be interpreted with caution appropriate for a null result, clear additivity of these two factors is consistent with a dissociation between prospective and retrospective contributions to sense of control. We suggest that the experience of control in normal circumstances represents a sum of these two independent components.

Together, our results suggest action selection processes contribute prospectively to the sense of control. This view is compatible with a number of models of action selection. In one influential model, action selection involves a hierarchical process of generating intentions which increase in specificity (Pacherie, 2000, 2008; see also Chambon et al., 2011). In our case, primes provide a first specification of which keypress to perform. When the subsequent target is compatible, the process of specifying the intention is fluent and facilitated, relative to incompatible conditions. Alternatively, other recent models treat intention as parallel competition between alternative premotor representations (Cisek, 2007). In such models, strength of an intention depends on how much its activation level exceeds that of alternatives. Compatible primes might increase sense of control in our task either by facilitating the processes that develop intentions, or by boosting the final activation level of an intention, or both. Importantly, however, in both models, the sense of control depends on processes that occur *before* action initiation, and makes no reference to the effects of action. In this sense, feeling of control is partly prospective, rather than effect-related.

We propose a model of prospective sense of control that captures these constraints. Once an intentional code for left or right action has been fully specified by the subliminal prime, it is transferred to temporary storage in an "intentional buffer" (Fig. 6b). Importantly, this intentional buffer is not altered by the subsequent process of confirmation, or by the auto-inhibition that occurs in the NCE. We suggest that the prospective contribution of action selection to sense of control arises from merely reading out the intentional buffer, in advance of the action itself and before the moment where NCE operates. Under normal circumstances, the prospective feeling of control read from the buffer would be rapidly followed by the resulting action and the predicted effect. Only once action and effect have occurred, can the classic mechanisms of action-effect comparison begin. These mechanisms involve additional retrospective processes. For example, the contents of the intentional buffer may be compared with the action and its external effect, resulting in the subject not feeling responsible for the effect when a mismatch occurs (e.g., Farrer et al., 2008; Sato & Yasuda, 2005).

Although this is necessarily speculative, there is convergent evidence suggesting the existence of such a buffer. Computational models of motor control as applied to sense of agency have demonstrated that computing agency requires matching forward model predictions with sensory feedback (e.g., Blakemore, Frith, & Wolpert, 2001). The predictions are available instantaneously, but the sensory feedback is delayed. Because of this delay, the predictions made by the forward model must be buffered until the feedback becomes available, ensuring that the matching process uses the correct temporal alignment. This buffer component was very explicit in earlier versions of these models (e.g., Miall, Weir, Wolpert, & Stein, 1993), though it receives less attention in more recent incarnations. In our suggestion, it is not the outcome prediction of the forward model that is buffered, but the processing of action selection itself (i.e., the so-called "inverse model"). However, our suggestion of buffering premotor signals is essentially similar.

Interestingly, the prospective contribution of selection fluency to sense of control in our experiment is strictly illusory. The relation between participant's actual behaviour and subsequent outcomes was the same whether primes were compatible or not. Therefore, compatible and incompatible conditions did not differ in the level of actual control, in the statistical sense that action-outcome contingency was similar for compatible and incompatible conditions. Yet, when subjects were asked to explicitly elaborate on how they judged control during post-experiment debriefing, none of them mentioned the fluency, or ease of compatibly-primed actions. Rather, most participants reported trying to focus on the colour of effects or on action-effect intervals, and occasionally reported "magical thoughts" (e.g., "I though the harder I pressed the button response, the more in control I was of when the colour patch appeared"). Internal signals of premotor fluency might not produce a strong conscious experience with distinctive content, but might influence the experience of surrounding events. Thus, fluency of action selection would not be experienced as such, but would presumably be experienced as something that goes 'right' or 'wrong' in the control of instrumental action, and thus seems relevant to sense of agency. However, the fact that the experience of fluent selection cannot be explicitly reported or experienced, does not prevent the brain from using fluency signals to form an experience of agency (Chambon et al., 2012). In that sense, signals relating to the fluency of action selection would not be perceived for what they really are, but (mis-)attributed to the processes of actually controlling the action.

The large literature on sense of agency confirms that multiple cues, including statistical contingency (Moore, Lagnado, Deal, & Haggard, 2009), temporal contiguity (Farrer et al., 2008), and prior expectation (Wegner, 2002) all contribute to sense of agency. But people seem to have relatively little explicit knowledge of *how* they compute agency, suggesting that this multiple cue integration process is largely automatic. Fluency signals arising from action selection processes may combine, at an implicit level, with several others cues, to produce a reliable sense of agency. In routine situations, for example, fluent action selection and control of action effects generally co-occur. Thus, the skilled pilot immediately knows which button in a complex cockpit must be pressed to deal with each specific type of incident: her extensive training means that she automatically plans a specific response appropriate to the current situation, and knows that the aircraft will respond appropriately. Outside the laboratory, fluent action selection is often a good *advance predictor* of actual statistical control over the external environment. By separating fluency of action selection from actual control contingencies, we have demonstrated the importance of this prospective aspect of agency. In future research, we will investigate whether this prospective aspect of agency is overwritten when we actually lose control, for example if the actual outcome of our action is not as predicted. We expect that the healthy brain successfully integrates prospective feelings of control based on action selection, and retrospective judgements of actual control over action outcomes. However, this integration process may fail in some circumstances, as it might be the case in psychiatric patients suffering from delusions of control.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2012.07.011.

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