Integrating prospective and retrospective cues to the sense of agency: a multi-study investigation[†]

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Abstract

Sense of agency (SoA) refers to the experience of voluntary control over one's own actions, and, through them, over events in the outside world. Recent accounts suggest that SoA involves an integration of various cues. These include prospective cues, for example, related to the fluency of action selection, and retrospective cues, linked to outcome monitoring. It remains unclear whether these cues may have independent effects on SoA, and, in particular, how their relative contributions may change during instrumental learning. In the present study, we explored these issues by conducting a multi-study analysis of seven published and unpublished studies on the role of prospective cues to the SoA. Our main question was how the effects of selection fluency on SoA might change as information about action–outcome contingencies is gathered. Results show that selection fluency can have a general and consistent influence on the SoA, independent of outcome monitoring. This suggests selection fluency is used as a heuristic cue, to prospectively inform our SoA. In addition, our results show that the influence of selection fluency on SoA may change systematically as action–outcome contingencies are gradually learned. We speculate that dysfluent selection may impair formation of mental associations between action and outcome.

Key words: agency; intention; volition; metacognition; multi-study analysis

Introduction

Our experience of voluntary action is normally accompanied by a sense of agency (SoA), that is, a feeling that we are in control of our actions and, through them, of events in the outside world (Haggard and Tsakiris 2009). Usually, the SoA exists in the background of our mental lives, but we become especially aware of it when there is a disruption in the chain of events of voluntary action (Chambon et al. 2014; Gallagher 2012): SoA emerges from establishing a link between our intentions, actions, and external outcomes. However, the details of how these sources inform SoA remain unknown.

Many studies have focused on the role of monitoring the consequences of our actions. These have shown that an important aspect of the SoA relies on a comparison between predicted or expected outcomes and actual action outcomes (Blakemore et al. 2002; Wegner and Sparrow 2004). Specifically, when there is a mismatch, the SoA is reduced. While this comparison may rely on predictive signals, this process is essentially *retrospective*, as it depends on knowing the action outcomes.

Recently, it has been shown that there is also a *prospective* contribution to the SoA, based on the metacognitive monitoring of action selection processes, that is, linking intentions to action (Chambon et al., 2014). These studies used subliminal priming of actions to manipulate the ease of action selection in a simple

agency task (Chambon and Haggard 2012; Chambon *et al.* 2013, 2015; Sidarus *et al.* 2013, 2017; Voss *et al.* 2017; Wenke *et al.* 2010). Summarily, participants made a left or right hand action in response to a target arrow, and a coloured circle appeared after a variable delay. Participants then judge how much control they felt over these circles. Importantly, a prime arrow was briefly presented just before the target, unbeknownst to the participants. Action selection was easy when prime and target directions were congruent; but if the prime was incongruent with the target, this created a response conflict, which impaired action selection, leading to slower response times and more errors. Results showed that incongruently primed actions led to a lower SoA over action outcomes, than congruently primed actions (Wenke *et al.* 2010). Similar effects have also been shown using supraliminal stimuli (Sidarus and Haggard 2016; Sidarus *et al.* 2017; but see Damen *et al.* 2014). Thus, the fluency, or ease, of action selection, can inform the SoA prospectively, and long before the outcome is known.

In the subliminal priming task, participants were not aware that selection fluency was manipulated, nor did they strategically decide to use fluency as a cue to agency (Wenke *et al.* 2010; Chambon and Haggard 2012). Although the experience of selection fluency/dysfluency may be relatively weak, people may have a sense of 'something going wrong' in incongruent trials, even without being able to identify why they have this feeling (Pacherie 2008; Morsella *et al.* 2009; Desender *et al.* 2014). This feeling could in turn become associated with subsequent events, such as action outcomes. In fact, response conflict has been suggested to serve as an aversive signal (Botvinick 2007), and can lead to more negative judgements of neutral stimuli (Fritz and Dreisbach 2013).

Importantly, recent models of the SoA emphasize that it involves the integration of multiple signals, which may become available at different stages of voluntary action (Moore and Fletcher 2012; Farrer *et al.* 2013; Synofzik *et al.* 2013; Chambon *et al.* 2014). Monitoring of action selection can provide an initial, prospective cue to SoA. Forward model predictions about the outcome can then be compared with the observed outcome once this becomes available, to retrospectively link action and outcome.

This raises the question of how prospective and retrospective cues are integrated. On one view, integration follows the principles of optimal cue integration (Moore and Fletcher 2012; Synofzik *et al.* 2013): cues are weighted based on their reliability, thus more reliable cues have a stronger influence than less reliable cues. Additionally, the weighting of cues may be altered by prior knowledge, or contextual cues. This approach has previously proved useful to understanding cue integration in SoA (Moore and Haggard 2008; Wolpe *et al.* 2013). Yet, how the weighting of different cues may change dynamically with experience, for example, throughout the process of learning new action–outcome contingencies, remains poorly understood.

Moreover, it has been suggested that selection fluency may become a useful cue to SoA because it is predictive of successful action (Haggard and Chambon 2012; Chambon *et al.* 2014). Our main question here was whether using selection fluency as a cue to SoA may be a general heuristic learned from everyday experience, similar to other fluency effects known in the metacognition literature (Alter and Oppenheimer 2009). Alternatively, the relation between selection fluency and particular outcomes might need to be acquired in specific contexts, in order to inform SoA.

In the present study, we investigated the integration of prospective and retrospective cues to SoA, based on action

selection and outcome monitoring, respectively. More specifically, we assessed how the contribution of selection fluency to SoA may change during instrumental learning, as information about action–outcome contingencies is gathered. For this, we conducted a multi-study analysis, combining currently known studies on prospective cues to the SoA.

Our measure of SoA—agency ratings—was obtained by asking participants to judge how much *control* they felt over action outcomes (see Supplementary Material for detailed instructions). Although the terms 'sense of agency' and 'sense of control' have previously been distinguished in the literature (Pacherie 2008), we will use these terms interchangeably. We consider the 'sense of control' as an aspect of our experience of agency, assessing the *instrumental* relation between actions and outcomes, rather than focusing on the *attribution* of outcomes to particular agents (Chambon *et al.* 2014).

In these studies, three cues to SoA were varied (Fig. 1A). Selection fluency was manipulated by varying the congruency between primes, or flankers, and the executed action. The action was followed by a variable action–outcome interval (AOI). The action outcome (one of several coloured circles) depended on the action and congruency conditions (100% contingent). Therefore, in each trial, these three cues could be combined to inform agency ratings (our measure of SoA). Since action–outcome relations had to be learned anew in each block of trials, tracking changes in agency ratings across trials indexed the contribution of monitoring outcome identity (i.e. the colour).

Importantly, the relative contribution of these three cues to SoA could be modulated by contextual information, such as instructions. If participants are instructed to focus on a particular cue to SoA, e.g. outcome identity, the contribution of that cue to SoA would likely increase overall. Additionally, this could also alter the contribution of the other cues to SoA. Within the experiments analysed here, there were two groups of studies that
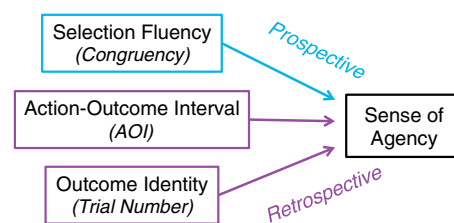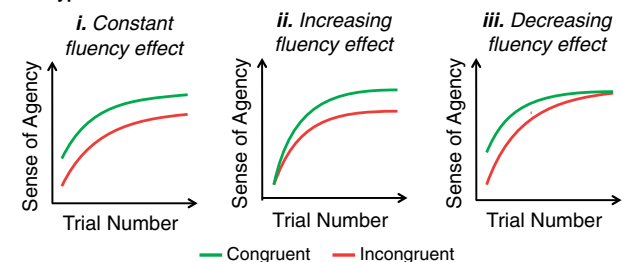

Figure 1. Rationale for the study. (**A**) Prospective and retrospective cues to the SoA, with their presumed corresponding variables investigated here (in italics). (**B**) Schematic of hypothetical results for the interaction between selection fluency and trial number, assuming that repeated exposure to actions and outcomes will influence SoA. As knowledge about action–outcome contingencies is gathered (across trials), the effect of selection fluency on SoA might: (i) remain constant; (ii) increase; or (iii) decrease .

differed in the instructions given to participants about the agency ratings procedure. The studies in Group 1 instructed participants to focus on the relation between actions and outcomes, that is, to focus on outcome identity. Studies in Group 2 instructed participants to focus on when outcomes appeared, that is, to focus on AOI (see Table 1 in Methods, and Supplementary Material for instruction examples).

We suggest 4 different accounts may be hypothesized regarding the relation between selection fluency and outcome identity, which would be consistent with three patterns of results for how the effect of selection fluency on agency ratings may change across trials (Fig. 1B). We assume that participants attended to action–outcome relations, and thus predict that agency ratings would increase across trials. Even if participants were not directly instructed to attend to outcome identity (as in Group 2 studies), we still predict that they would track action–outcome contingencies, at least implicitly, as it would help predict the upcoming outcome.

1. *Generally prospective.* Selection fluency is a heuristic that is generally used to prospectively inform SoA, independent of outcome monitoring. In this case, the effects of selection fluency on SoA would remain constant across trials [pattern (i)]. Since this account does not predict an interaction between selection fluency and context-specific action–outcome learning, it would be equally plausible under conditions in which there is no learning about outcomes, and thus no increase in agency ratings (unlike subsequent accounts).
2. *Learning to be prospective.* As we learn specific action–outcome relations in each block, we also learn to associate fluency with specific outcomes. Thus, we become able to use selection fluency as a proxy for causing a given outcome. This account predicts that the effects of selection fluency on SoA would increase across trials [pattern (ii)].
3. *Prospective effects on learning.* Selection fluency impacts on the learning of action–outcome associations. Learning to associate dysfluent actions to their outcomes may be impaired, relative to learning about the outcomes of fluent actions. In line with this, sensorimotor predictions of action consequences can be disrupted by incongruent subliminal priming of actions (Stenner et al. 2014, 2015). As fluent actions are well linked to their outcomes, agency ratings increase steeply, whereas dysfluent actions are more slowly associated with their outcomes. This account predicts that the effects of selection fluency on SoA would increase across trials [pattern (ii)].
4. *Optimally prospective.* We rely on the heuristic of selection fluency as a cue to SoA to prospectively guide our SoA at the start of a block, when outcomes are not a reliable cue. Once

enough knowledge is gathered about action–outcome contingencies, outcomes will be a more reliable cue to SoA. Therefore, the effects of selection fluency on SoA should decrease across trials [pattern (iii)].

Notably, accounts 2 and 3 predict the same pattern of results (i), but for very different reasons. While these may be prove difficult to dissociate, it is worth noting that the 'learning to be prospective' (2) account would not be compatible with the heuristic account (1), since it implies that selection fluency is exclusively learned in a context-specific manner. Moreover, learning about action–outcome contingencies would be a pre-requisite for any effects selection fluency on agency. In contrast, the possible influence of selection fluency on learning (account 3) would still be compatible with using selection fluency as a heuristic cue to agency in different contexts. In fact, such influences on learning could be part of mechanisms underlying the development of the learned heuristic relation between selection fluency and SoA.

Finally, it is worth considering the role of AOI. This was manipulated in the experiments considered, in order to increase variability in SoA, and prevent ceiling effects on ratings (Haggard et al. 2002; Wenke et al. 2010). No significant interactions have been found between selection fluency and AOI so far. However, the relation between AOI and outcome identity is less clear. Longer delays are typically associated with a weaker SoA (Farrer et al. 2013), possibly due to short AOIs being strongly associated with the typical windows of motor control. Therefore, short intervals may generally lead to stronger SoA than long intervals, regardless of knowledge about outcome identity. Yet, AOI may also compete with outcome identity in driving SoA. A focus on outcome identity, as instructed in Group 1, may reduce the contribution of AOI to SoA. In contrast, if participants are instructed to focus on AOI, as in Group 2, outcome identity may become less relevant to SoA. This would predict a reduced influence of outcome identity on SoA, and thus a smaller change in agency ratings across trials.

Materials and Methods

Experimental design

The behavioural tasks are described in detail in each respective publication; the common design features are depicted in Fig. 2. In Experiments 2–4 (Sidarus and Haggard 2016), the Eriksen flanker task (Eriksen and Eriksen 1974) was combined with the aforementioned agency task. Participants responded to a central target letter, and response conflict was induced when the flankers were incongruent with the central target (e.g. HHSHH). A list of the studies included is provided in Table 1. This table

Table 1. Factorial design and differences between studies

Publication	Group	Experiment number	Manipulation	AOI (ms)	Number of outcomes[a]	Number of trials	Number of blocks
Sidarus et al. (2017)	1	1	Subliminal priming	400, 600	8	64	8
Sidarus and Haggard (2016), Experiment 1	1	2	Supraliminal flankers	100, 300, 500	4	72	4
Sidarus and Haggard (2016), Experiment 2	1	3	Supraliminal flankers	200, 400	8	64	8
Sidarus and Haggard (2016), Experiment 3	1	4	Supraliminal flankers	100, 500	4	64	12
Chambon et al. (2013)	2	5	Subliminal priming	100, 300, 500	4	48	4
Voss et al. (2017)	2	6	Subliminal priming	100, 400, 700	8	56	8
Chambon et al. (2015)	2	7	Subliminal priming	100, 400, 700	4	36	2

[a]This refers to the number of outcomes (coloured circles) per block. In Experiment 4, there were 12 coloured circles overall, but only 4 in each block.
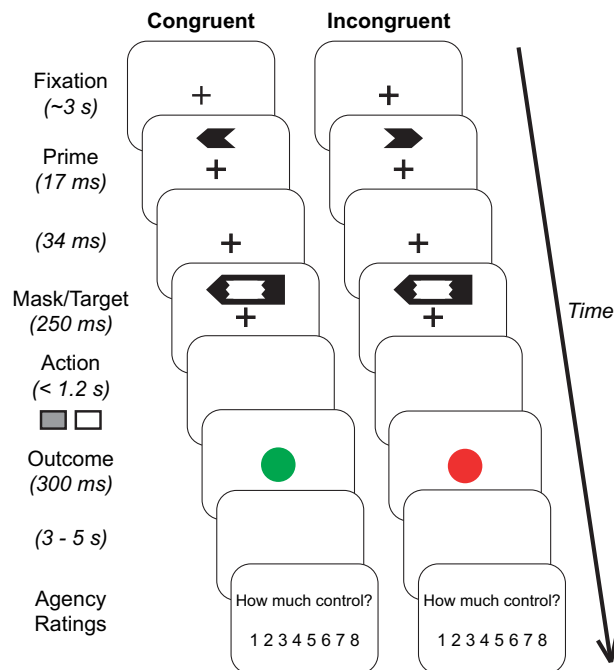
Figure 2. Task outline for the subliminal priming studies (adapted from Chambon et al., 2013). This outline is similar to experiments from Group 1. Critically, all studies involve a target, which calls for a left- or right-hand action. This is followed by a coloured circle (the outcome), after a variable delay. Participants give agency ratings over the outcome, at the end of each trial. In studies with supraliminal flanker, targets consist of one of two letters, which appear surrounded by congruent (e.g. SSSSS), or incongruent (e.g. HHSHH), flankers.

further lists the grouping of experiments, and relevant differences between the studies. In addition to the differences listed, experiments in Group 1 used a 9-point Likert scale, whereas studies in Group 2 used an 8-point scale.

Study selection for multi-study analysis

Of all the known studies that have manipulated action selection and obtained a measure of agency, three were excluded from our analysis. One study only obtained agency judgements at the end of each block (Wenke *et al.* 2010). Another study only had two outcomes, therefore did not require much action–outcome learning (Damen *et al.* 2014). Finally, detailed trial-wise data were not available from one study (Chambon and Haggard 2012). Furthermore, we only included the relevant data from the available studies: for Exp. 2, we only used the data for the half of participants who gave agency ratings at the end of each trial, as the other half gave block-wise ratings. Also, we excluded trials from the neutral flanker condition. For Exp. 6, we only used data from healthy participants, as the others were clinical patients. For Exp. 7, we only used the data from the sham TMS (i.e. control) condition, since the other conditions involved active TMS stimulation.

Data analysis

Our main goal was to model the trial-wise control ratings as a function of selection fluency, AOI, and outcome identity, while appropriately accounting for the repeated measures over participants and experiments. We therefore estimated a three-level

multilevel model (e.g. Gelman and Hill 2006). More details are provided below.

To detect potential differences between experiments, and groups, we plotted the data for each experiment separately (see Figs 3 and 4 below). Notably, the absence of instrumental learning effects on agency ratings seen in Group 2 studies was unexpected, as it was assumed participants would intuitively track the relation between their action and outcome colours. This highlighted the critical difference in instructions, and motivated the grouping of experiments in the overall multilevel model according to the instructions. The exact experimenter, i.e. the person who gave the instructions, varied across experiments within each group, but the instructions remained consistent within each group.

Finally, we estimated the effects in separate multilevel models for each experiment, including all trials from each experiment, confirming the results presented here (see Supplementary Material).

Results

Considering how agency ratings changed across the trials, the data presented in Fig. 3 suggest an important distinction between the patterns of data obtained in the two groups of experiments. In Group 1 (Exp.: 1–4), agency ratings increased over trials, and the effect of congruency (higher agency ratings for congruent trials) increased as participants progressed through the trials, within a block. These patterns seemed largely absent in the data obtained from experiments in Group 2 (Exp.: 5–7): Agency ratings and the congruency effect remained broadly stable throughout the block.

We also considered the effect of AOI on agency ratings. The data presented in Fig. 4 suggest another important difference in the patterns of data between the groups of experiments: longer AOIs led to lower agency ratings in Group 2, but this pattern seemed to be absent in Group 1.

Before modelling the data, we limited the block length of each experiment to 36 trials per block in order to prevent any effects of trial number due to differences in block length across the experiments included in the meta-analytic model (Table 1).

Multilevel model of agency ratings

We modelled these data with a three-level multilevel logistic regression model (e.g. Gelman and Hill 2006), where the effects of trial, congruency, AOI, congruency by trial interaction, and congruency by AOI interaction were treated as varying between subjects and experiments, and as fixed effects (The model did not converge when we included the congruency by AOI interaction as a by-experiment random effect, so we dropped it. However, we estimated the full model including this term using Bayesian, and confirmed our results). Additionally, we interacted these effects with a group indicator variable at the fixed-effect level. The full fixed-effects specification of this model, along with estimated effects is shown in Table 2. Our main goals of inference were the differences in the data patterns observed in Figs 3 and 4; these effects are highlighted in bold in Table 2.

The use of multilevel modelling was motivated by acknowledging the hierarchical structure of the data, with repeated measures on individuals, and individuals within experiments, and the need to include continuous predictors at all levels of analysis. Additionally, the data were not balanced across individuals or experiments, because the sequence of congruent and incongruent trials within a block was randomized, further motivating the use of multilevel modelling. The model was fitted
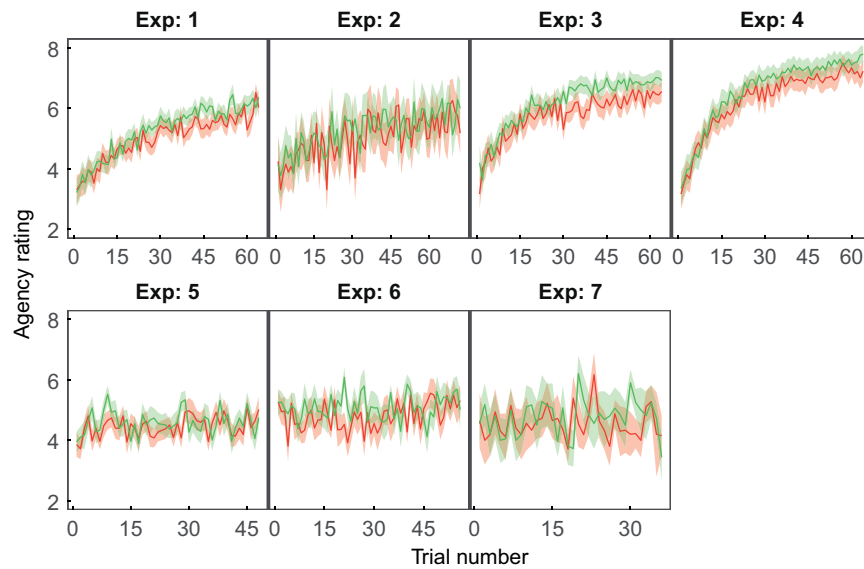
Figure 3. Mean agency rating across participants as a function of trial number, for each experiment ($\pm$ 1 SEM as shaded area). Top row = experiments from Group 1, bottom row = Group 2. Green = congruent, red = incongruent.
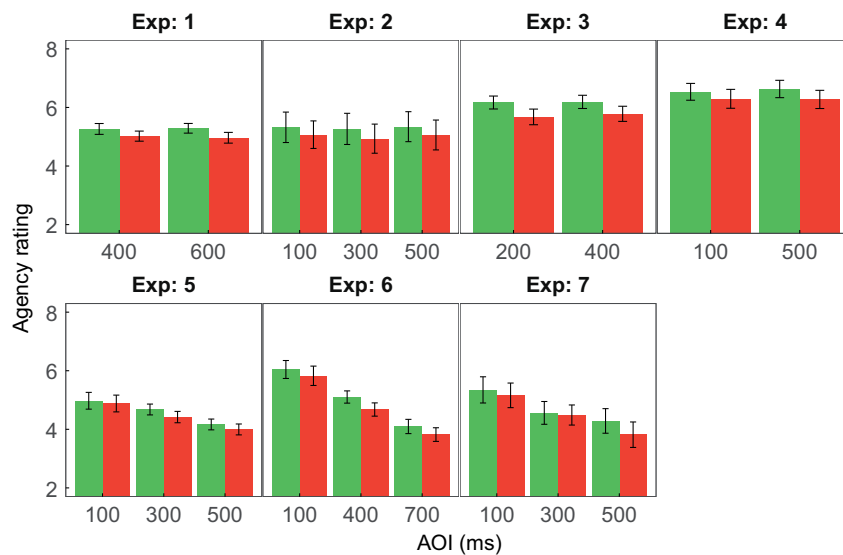
Figure 4. Mean agency rating as function of AOI for each experiment ($\pm$ 1 SEM). Top row = experiments from Group 1, bottom row = Group 2). Green = congruent, red = incongruent.

using the *lme4* package in the R statistical programming environment (Bates *et al.* 2014; R Core Team 2015).

Instead of modelling the agency ratings with a linear model, we treated them as proportions of the maximum rating, and therefore used logistic regression. This choice also allowed the model to naturally take into account the fact that the ratings are bounded at 1 and 9 (for Group 1; in Group 2, ratings were bounded at 8), and that the data showed a clearly curvilinear relationship between trial number and agency rating (for experiments in Group 1). We also modelled the data with a linear regression model with a quadratic term for trial number, and arrived at the same conclusions.

We used the following coding scheme for the predictor variables in the regression model: Group was dummy coded as 0 (Group 1) and 1 (Group 2), therefore all effects in Table 2 without

Group interaction denote average effects for experiments in Group 1. Trial was centred at trial 18, Congruency was coded as −0.5 (incongruent) and 0.5 (congruent); AOI denotes the effect of 100 ms increase in AOI, and was centred at 400 ms and used as a linear predictor—when using AOI as a factorial predictor, the model did not converge, and the data presented in Fig. 4 suggest that a linear effect in these ranges of AOI was a good approximation.

Regarding the main effect of congruency, the model (Table 2) showed a strong and robust effect of congruency on SoA for Group 1 (*main effect of Congruency*), with no noticeable difference in this effect for Group 2 (*Congruency by Group interaction*). AOI did not exert a detectable effect in Group 1 (*main effect of AOI*), but strongly decreased agency ratings in Group 2 (*AOI by Group*, general linear hypothesis test of AOI effect for Group 2: $b = -0.16$, $t_{(7)} = -7.83$, $P < 0.001$; Fig. 4 [Obtained using the

Table 2. Multilevel logistic regression model of agency ratings (estimates are log-odds). effects of primary interest are highlighted in bold

Effect	Estimate (SE)	Z	P	95% CI Lower	Upper
Intercept	0.39 (0.13)	2.97	0.003	0.13	0.65
Trial	**0.037 (0.0061)**	**6.1**	**<0.0001**	**0.025**	**0.049**
Congruency	**0.16 (0.028)**	**5.78**	**<0.0001**	**0.11**	**0.22**
AOI	**0.0067 (0.015)**	**0.44**	**0.66**	**−0.023**	**0.036**
Group	−0.12 (0.21)	−0.57	0.57	−0.53	0.29
Trial × Congruency	**0.0073 (0.0016)**	**4.65**	**<0.0001**	**0.0042**	**0.01**
Congruency x Group	0.012 (0.05)	0.25	0.81	−0.085	0.11
AOI × Group	**−0.17 (0.025)**	**−6.54**	**<0.0001**	**−0.21**	**−0.12**
Congruency x AOI	0.01 (0.0092)	1.08	0.28	−0.0081	0.028
Trial × Group	**−0.034 (0.0096)**	**−3.54**	**0.0004**	**−0.053**	**−0.015**
Trial × Congruency × Group	**−0.0093 (0.003)**	**−3.1**	**0.002**	**−0.015**	**−0.0034**
Congruency × AOI × Group	0.0075 (0.016)	0.46	0.64	−0.024	0.039

Note. Confidence intervals were obtained using the Wald method (Bates et al. 2014). '×' denotes interaction terms.
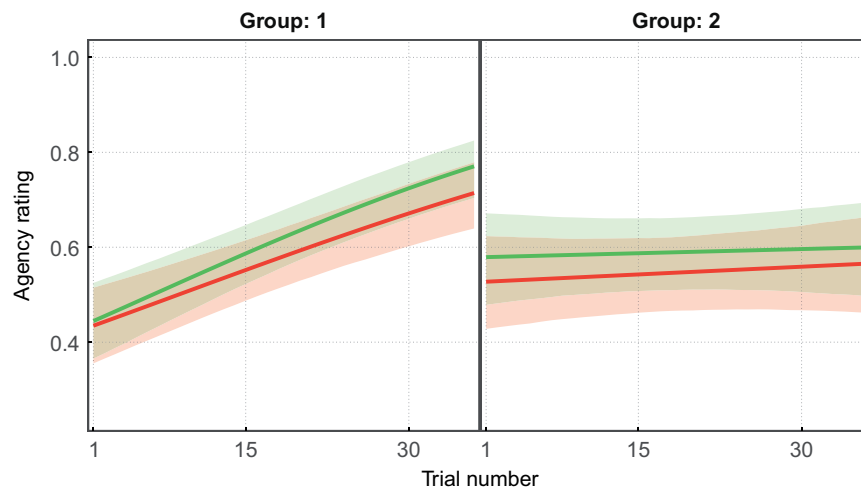

Figure 5. Multilevel logistic regression model of agency ratings. Predicted average agency ratings for each Group as a function of trial number (with 95% confidence intervals as shades around regression lines). Green = congruent, red = incongruent. Regression lines and CIs were obtained from 100000 simulations from the posterior distribution of plausible parameter values under uniform priors (Gelman & Su, 2015). Note the progressively increasing effect of congruency on agency in studies of Group 1, but not of Group 2.

model s estimated parameters and variance-covariance matrix. All tests were computed with a conservative 7 degrees of freedom (number of experiments)]. Importantly, there was no significant interaction between AOI and congruency for Group 1 (*Congruency by AOI*), nor for Group 2 (*Congruency by AOI by Group*). Although null results should be interpreted with care, these findings are consistent with the absence of interactions between congruency and AOI in other studies (Chambon and Haggard 2012; Sidarus *et al.* 2013).

Regarding the effect of outcome identity, agency ratings increased with trial number in Group 1 (*main effect of Trial*), but the effect was not statistically significant in Group 2 (*Trial by Group*, general linear hypothesis test of Trial effect for Group 2: $b = 0.003$, $t_{(7)} = 0.46$, $P = 0.66$). The effect of congruency increased with trial number in Group 1 (*Trial by Congruency*), but this interaction was not robust in Group 2 (*Trial by Congruency by Group*, general linear hypothesis test of Trial by Congruency for Group 2: $b = -0.002$, $t_{(7)} = -0.78$, $P = 0.46$). These effects are illustrated in Fig. 5.

Discussion

The present study investigated the relative contribution of prospective and retrospective cues to agency. Overall, a multi-study analysis of seven experiments showed a robust effect of the prospective—selection fluency—cue to SoA. These effects were consistent across different instructions regarding the agency ratings procedure, suggesting a general role of this prospective cue to agency. The different instructions did, however, modulate the contribution of the two retrospective cues—outcome identity and AOI. On the one hand, Group 1 experiments gave instructions to focus on learning action–outcome contingencies. These showed an increase in agency ratings across trials, as knowledge about the outcomes was gathered. Yet, no effect of AOI was found, suggesting that outcome identity drove agency ratings for Group 1. On the other hand, Group 2 experiments instructed participants to attend to AOI. These did not show a consistent change in ratings across trials, but did show effects of AOI on

ratings. Thus, for Group 2, AOI drove agency ratings, instead of outcome identity. These results suggest a trade-off between the two retrospective cues, and demonstrate the importance of contextual influences (e.g. instructions) in modulating cue integration in SoA. As it is our main interest, we will first consider the relation between prospective and retrospective cues.

Prospective versus Retrospective cues

For Group 1 studies, which focused on outcome identity, interactions with the prospective cue emerged. In addition to agency ratings increasing over time, we found a concurrent increase in selection fluency effects. There was a shallower increase over time in agency ratings for dysfluent actions (incongruent priming/flankers), relative to fluent actions (congruent priming/flankers). For Group 2 studies, which focused on AOI, there were no interactions between retrospective and prospective cues to agency. As there was no change in agency ratings across trials, selection fluency effects remained stable throughout. Dysfluent actions (incongruent priming) led to lower agency ratings than fluent actions (congruent priming) across trials. We will now evaluate the four possible mechanisms outlined in the introduction with regards to our results.

Generally prospective: selection fluency as a general heuristic

These findings clearly support the 'general heuristic' account described above: Selection fluency can serve as a heuristic cue to agency, which can be employed in novel circumstances, independently of one's knowledge about action–outcome contingencies [approximating pattern (i), in Fig. 1]. In Group 2 studies, we did not find a general increase in agency ratings, as predicted. Nonetheless, selection fluency was an important cue to SoA, and its effects were similar across trials.

These findings suggest that the relevance of selection fluency to agency is likely learned through everyday experience, rather than being specifically linked to any given environment. Regardless of a specific link between fluency/difficulty and particular outcomes, fluent action selection is more likely associated with desired or predicted outcomes than dysfluent selection. These findings are also consistent with the view that response conflict is an aversive signal (Botvinick 2007), with negative affective consequences that can affect subsequent events (Fritz and Dreisbach 2013). Relatedly, many studies have shown general influences of fluency/difficulty, e.g. in stimulus processing, on a variety of judgements, such as liking or familiarity (Alter and Oppenheimer 2009).

Learning to be prospective: fluency effects are not context-specific

The interaction between selection fluency and outcome identity observed for Group 1 studies might seem in line with the prediction of the 'learning to be prospective' account. This view proposes that we learn to use selection fluency as a cue to agency in a context-specific manner: we learn that fluent actions are associated with specific outcomes, and come to rely on selection fluency as a prospective proxy for the action outcome. From this perspective, there should be no fluency effects at the start of a block, because there is no *a priori* knowledge about how fluency informs SoA [pattern (ii), in Fig. 1B]. This was indeed the pattern observed in Group 1 studies (Fig. 5).

However, this account is incompatible with the general effects of selection fluency found in Group 2 (Fig. 5). In those studies, fluency effects were present from the start of a block, and independently of learning about outcome identity, as agency ratings did not consistently change across the block. Therefore, the relation between selection fluency and SoA had to be learnt in advance. Note that this does not preclude the possibility that the association between selection fluency and action outcomes could still be strengthened in particular contexts, and further enhance the contribution of prospective cues to SoA. For example, in complex tasks, e.g. sports, as expertise increases, greater fluency in action selection will typically be associated with greater accuracy in outcome prediction (Gray *et al.* 2007). Thus, the experience of fluency might gradually become an even more reliable advance predictor of action outcomes, and agency.

Prospective effects on action–outcome learning

The increased effects of selection fluency on agency across trials seen in Group 1 would also be consistent with the 'prospective effects on learning' account. From this perspective, outcomes that follow dysfluent actions would be less easily associated with their corresponding action, relative to outcomes that follow fluent actions. Assuming agency ratings would track action–outcome knowledge, ratings would increase more slowly for outcomes that followed dysfluent actions; thus, the difference in ratings relative to outcomes that followed fluent actions would increase. Such effects could result from action representations being disrupted by response conflict, and, in turn, be less effectively associated with outcomes. It may be adaptive to learn less about the consequences of dysfluent actions, than of fluent actions. For example, a novice playing darts who hits the bull's-eye at the first throw should recognise that this successful hit may have been partly due to luck. Her lack of practice with the game means her action selection was likely not very fluent or precise, and she is unlikely to easily replicate such an ideal hit.

Response conflict has been linked to lower confidence in one's action (Yeung and Summerfield 2014), as the difference in the accumulation of evidence between the (ultimately) selected and unselected responses is reduced. This degraded or disrupted action signal might thus be harder to associate with ensuing outcomes. Selection fluency can also disrupt sensorimotor predictions (Stenner *et al.* 2015), and thus potentially alter action–outcome linkage. Response conflict may also serve as an aversive signal, and can alter the valence of ensuing neutral events (Fritz and Dreisbach 2013). This negative affect could also impair the associative process. Interestingly, this view would suggest that selection fluency effects previously found with block-wise agency ratings (Wenke *et al.* 2010) could result from better or worse associative links between particular outcomes and their corresponding actions.

Importantly, this hypothesis remains speculative, given a present scarcity of research on how selection fluency/conflict may influence learning. As the present studies asked participants about their SoA, it can only offer indirect information about instrumental learning. Finally, under the instructions to focus on outcome identity, agency ratings may have been very low at the start of a block, since participants did not have any outcome information yet. This floor effect could thus have masked the general, and typically stable, influence of selection fluency on agency (seen in Group 2 studies), which then gradually emerged as outcome knowledge was gathered, and ratings started to vary. Further research is clearly needed to further test this hypothesis, namely by directly testing knowledge about

action–outcome associations, or obtaining more objective measures of instrumental learning.

Optimally prospective: no reduction in fluency effects

The present results seem to rule out the 'optimally prospective' account. Assuming prior knowledge about the relation between selection fluency and SoA, this account suggests that we rely most on selection fluency as a cue to agency when other cues are unreliable/unavailable. An optimal cue integration account (Moore and Fletcher 2012; Synofzik *et al.* 2013) would have predicted that the prior reliability of the selection fluency cue could have served to compensate for the low reliability of outcome identity at the start of a block. Its contribution to SoA might then reduce with outcome learning, assuming agency ratings would have been tracking outcome identity [hypothesis (iii), in Fig. 1]. In contrast, results showed either a constant (Group 2) or an increasing (Group 1) contribution of selection fluency to SoA across trials. These findings question the use of an optimal integration across *all* cues to SoA (Sidarus *et al.* 2013), although it may apply when integrating *some* cues. Current proposals do not easily account for changes in reliability over time, such as those found for outcome identity during instrumental learning. Moreover, it remains unclear how these processes can handle the integration of cues that become available at different times *within* a trial, e.g. prospective vs. retrospective.

Competition between retrospective cues

Returning to the relation between the two retrospective cues, outcome identity and AOI, it could be argued that the apparent trade-off, or competition, between the two cues could be partially attributed to differences in the salience of the AOI cue. Variability may have been less salient in most experiments that were part of Group 1, as three out of four used only two intervals, whereas experiments in Group 2 always used three intervals (Table 1). However, similarly to those experiments, and others (Chambon and Haggard 2012; Sidarus *et al.* 2013), three AOIs were used in Experiment 2 (Group 1), but no significant effect of AOI was found (see Table S2 in Supplementary Material). Therefore, the difference in instructions between the groups of studies likely played a more critical role in the relative weighting of the retrospective cues.

When participants were instructed to use AOI as a cue, and given the prior association between short intervals and stronger SoA (Farrer *et al.* 2013), this may have seemed a more reliable cue to SoA, relative to outcome identity. The availability and relevance (given the instructions) of this cue to agency could have, in turn, reduced the learning of action–outcome associations. It is worth noting that the learning of action–outcome associations in these studies could be difficult, even when only 4 colours appeared in each block (as in Exps 5 and 7). In the subliminal priming paradigm, participants could learn that two colours were associated with each hand, but could not further disambiguate those two colours. Outcome colours depended both on the action performed, and on prime-action congruency, and this latter information was not available since primes were subliminal. On the other hand, in studies with supraliminal flankers, congruency information was explicitly available, which could have facilitated action–outcome learning. Whereas all studies in Group 2 used subliminal priming, and three of four studies in Group 1 used supraliminal flankers (Table 1), one might wonder whether differences in learning effects across groups of studies could explain the different role of outcome

identity to SoA. However, in Experiment 1 (of Group 1) an increase in agency ratings over time was found (see Table S1 in Supplementary Material) despite using subliminal priming, and having eight outcome colours per block (due to another factor in the experiment). This further supports a role for instructions.

Nonetheless, while this trade-off may emerge due to instructions, other contextual cues could also have an impact. A study which used similar instructions to those in Group 2 reported both an effect of AOI and of outcome identity on agency ratings (Sidarus *et al.* 2013), with no significant interaction. Moreover, an interaction between outcome identity and selection fluency was found. However, this study involved a lower action–outcome contingency (67%), than the studies considered here (100%). As outcome predictions were sometimes violated, a stronger intrinsic motivation to attend to outcome identity may have been engaged. This motivation may have been partially absent in the studies of Group 2 investigated here, as outcome identity was fully contingent on action. Alternatively, if outcome identity is highly reliable, given prior training, this may be a predominant cue to SoA (Evans *et al.* 2015). Therefore, interactions among retrospective, or between retrospective and prospective cues to agency, can be contextually modulated not only by instructions, but also by the requirements of the task at hand.

Integrating multiple cues

Our findings demonstrate the robust role of action selection fluency as a prospective cue to the SoA. We suggest that prospective cues serve as a heuristic cue to estimate agency, learned from everyday life, in which selection fluency is typically associated with expertise in a task and, in turn, successful action. They further highlight the integrative nature of SoA, combining multiple cues, from low-level sensorimotor information, to higher-level beliefs. Notably, contextual information may highlight particular cues, and alter the relative weights of various cues. These cues may also become available at different times, thus prospective cues about the action are integrated with retrospective information about action outcomes. While these may interact in some contexts, they may also make independent contributions to SoA (Sidarus *et al.* 2017).

The cues discussed here are but a few of those relevant to SoA (Synofzik *et al.* 2013). For example, the subjective experience of freedom in choosing one's actions is considered an important component of SoA (Pacherie 2008). Choosing freely has been associated with greater SoA than following instructions (Wenke *et al.* 2010; Barlas and Obhi 2013; Caspar *et al.* 2016; Khalighinejad *et al.* 2016; Sidarus *et al.* 2017). Moreover, the 'what, when and whether' model proposes that voluntary action involves different components: what action to perform; when; and whether to go ahead with a planned action (Brass and Haggard 2008). In fact, SoA is influenced not only by whether we have a choice in what to do, but also by whether there is consistency in 'what' and 'when' decisions being specified internally versus externally (Wenke *et al.* 2009). Here, primes (or flankers) were used to manipulate the fluency, or difficulty, of 'what' decisions. Additionally, in three of the seven experiments (Exps 1, 3 and 6) included here, a mix of free- and instructed -choice trials was used, which were pooled in the present analyses. In free-choice trial participants could choose whether to press the left- or right-hand key; in instructed-choice trials they had to respond according to the stimuli (as in the remaining experiments). Experiments 1 and 6 (from Groups 1 and 2, respectively) involved subliminal priming, and

Experiment 3 involved supraliminal flankers. Here, we found consistent effects of the biasing stimuli (primes and flankers) on participants' actions (and biases on their 'free' choices). Whereas there was some effect of choice on SoA in Experiment 1, it was not very robust (cf. Sidarus *et al.* 2017), and choice did not affect SoA in Experiments 3 and 6. Thus, it remains unclear which factors may modulate the effect of choice on SoA. More importantly, for the present analyses, despite differences in stimuli, instructions and experimenters, selection fluency (i.e. congruency between the biasing stimuli and the participant's action) had a similar effect on agency ratings for both free- and forced-choice trials (Sidarus and Haggard 2016; Sidarus *et al.* 2017; Voss *et al.* 2017). Consequently, the effect of choice on SoA is independent from the effect of selection fluency (see also Wenke *et al.* 2010).

It has also been proposed that SoA is multi-factorial, and that different cues may influence different aspects of SoA. Whereas, the feeling of agency is a non-conceptual representation, derived from low-level, sensorimotor signals; the judgement of agency is a propositional representation, which further integrates conceptual information, such as context and beliefs. It remains unclear whether selection fluency, or response conflict, might influence the SoA at the non-conceptual or the propositional level. Selection fluency may affect the SoA through the emergence of signals from action monitoring processes (see Sidarus *et al.* 2017). Such signals could be integrated with outcome monitoring signals at the more low-level, feeling of agency (Stenner *et al.* 2014). It has been shown that we have metacognitive access to conflict signals induced even by subliminal stimuli, and that the experience of conflict influences cognitive control processes (Desender *et al.* 2014). Yet, this experience of fluency/conflict may be a type of metacognitive 'epistemic feeling' (Arango-Muñoz 2010), which are typically vague in content and hard to attribute to specific sources (Winkielman *et al.* 2015). These epistemic feelings could thus influence other processes, such as SoA, at a non-conceptual, non-propositional level. Nonetheless, it remains possible that the influence of fluency/conflict on SoA relies on propositional representations, with the experience of fluency only being integrated at the level of judgements of agency. Further research is clearly needed to clarify the integrative and multi-factorial nature of SoA.

Conclusions

The present investigation has shown that action selection fluency can serve as a heuristic cue to prospectively inform our SoA. The experience of agency may already begin even before the action. This prospective SoA may serve as a general advance predictor of successful action, and to bridge the interval between action and outcome. Importantly, the SoA requires a complex integration of multiple cues, from multiple sources, available at different times. Prospective and retrospective cues can have independent effects on SoA. Nonetheless, depending on contextual cues, such as instructions, or task requirements, the relative contribution of these two cues to SoA may also be dynamically changed during instrumental learning. We speculate that dysfluent action selection may weaken the link between action and subsequent outcome.

Supplementary Data

Supplementary data is available at *Neuroscience of Consciousness* online.

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