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Short Communication

# Prime and probability: Causal knowledge affects inferential and predictive effects on self-agency experiences

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ABSTRACT

Experiences of having caused a certain outcome may arise from motor predictions based on action–outcome probabilities and causal inferences based on pre-activated outcome representations. However, when and how both indicators combine to affect such self-agency experiences is still unclear. Based on previous research on prediction and inference effects on self-agency, we propose that their (combined) contribution crucially depends on whether people have knowledge about the causal relation between actions and outcomes that is relevant to subsequent self-agency experiences. Therefore, we manipulated causal knowledge that was either relevant or irrelevant by varying the probability of co-occurrence (50% or 80%) of specific actions and outcomes. Afterwards, we measured self-agency experiences in an action–outcome task where outcomes were primed or not. Results showed that motor prediction only affected self-agency when relevant actions and outcomes were learned to be causally related. Interestingly, however, inference effects also occurred when no relevant causal knowledge was acquired.



## 1. Introduction

In most humans, the performance of behavior is often accompanied by a sense of self-agency, that is, the experience of causing one's own actions and resulting outcomes. These experiences arise under conditions in which the cause of outcomes is clear, such as when one knows that one's own action leads to the outcome, but also when self-causation is more ambiguous, such as when the outcome may occur independently of one's own action. Accordingly, the literature distinguishes two main processes that contribute to experiences of self-agency (e.g., Moore & Haggard, 2008; Moore, Lagnado, Deal, & Haggard, 2009). First, experiences of self-agency depend on the extent to which our motor control system is able to predict the sensory outcome that is produced by performing a specific action. Second, self-agency can be cognitively inferred, based on whether the outcome corresponds with the outcome we had in mind.

So far, however, research has not clearly addressed when and how motor predictions and cognitive inferences combine to affect experiences of self-agency. Based on previous research on the effects of prediction and inference on self-agency (Sato, 2009), we propose that the influence of motor predictions and cognitive inferences on experiences of self-agency crucially depends on knowledge people have about the causal relation between actions and outcomes. Such causal knowledge refers to the information that a person has to assess the consequences of a specific action. Basically, this knowledge is obtained when the motor control system learns that the execution of a specific motor command leads to a specific sensory outcome. One can learn such a relation through direct performance of an action and subsequent observation of the outcome, but also

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through instruction if one is able to imagine or simulate the action and the outcome. Whereas the acquisition of causal knowledge of action–outcome relations is likely to be facilitated by conscious processes, e.g., in case of mental imagery (e.g., Frith, Blakemore, & Wolpert, 2000; Jeannerod & Frak, 1999), recent work suggests that the learning of this knowledge may occur without conscious awareness (Custers & Aarts, 2011).

Once a person has acquired causal knowledge about a certain action–outcome relation, this knowledge may influence the effects of both motor predictions and cognitive inferences on people's experiences of self-agency over these action–outcomes (Synofzik, Vosgerau, & Newen, 2008). That is, when people know that actions and outcomes are causally related (e.g., due to a high probability of co-occurrence), both motor-predictive and cognitive-inferential processes affect self-agency (Moore & Haggard, 2008). However, knowing that specific actions and outcomes are not causally related prevents the contribution of both motor predictions and cognitive inferences to experiences of self-agency over these specific outcomes, since this knowledge informs people about whether they may have caused this outcome by their own action. Yet, if people do not have relevant knowledge about the causal relation between the specific action and outcome at hand, the motor control system cannot predict the sensory consequences of the action, whereas inferences may still augment the sense of agency when the outcome corresponds with the outcome presaged in one's mind. We report an experiment that tested this novel and intriguing idea.

Central to the motor prediction view on the emergence of self-agency is the relation between our actions and outcomes. When we perform a specific action (e.g., pushing a button) that is expected to produce a specific outcome (e.g., turning on a light), we do not only have knowledge and cognitions about their causal relation. Our motor control system also predicts the sensory consequences of that action (e.g., Blakemore, Wolpert, & Frith, 2002; Moore & Haggard, 2008). These motor prediction processes, in which predicted and actual sensory outcomes are being compared, are crucial to regulate behavior. Furthermore, when a match is detected between the predicted and the actual outcome, we experience a sense of self-agency over causing the outcome. However, the absence of such a match produces weaker experiences of self-agency. Thus, the better the motor control system can predict the sensory consequences of a specific action, the more likely it becomes that the actual sensory outcome of an action matches the predicted sensory outcome and that one feels a sense of self-agency over producing this outcome. Hence, causal knowledge plays an important role in prediction effects on self-agency experiences. (Moore & Haggard, 2008; Moore, Lagnado, et al., 2009).

In addition to motor predictability influences, research has shown that cognitive inferences play a key role in our experiences of self-agency. Specifically, this research shows that people tend to infer self-agency when the outcome corresponds with the outcome they had in mind (Wegner, 2002). Often, this inference effect results from our intention to produce a specific outcome. Interestingly, experiences of self-agency are also enhanced when people do not intend to produce a specific outcome, as long as a representation of the action–outcome is pre-activated (e.g., Wegner & Wheatley, 1999). That is, (subliminal) priming of outcome representations before performing an action and observing the corresponding outcome also enhances people's experiences of self-agency (e.g., Aarts, Custers, & Wegner, 2005; Ruys & Aarts, in press; Sato, 2009). These inference effects of outcome priming are suggested to occur independently of actual action execution or motor predictability and rely merely on pre-activated outcome representations (e.g., Wegner, 2002; Wegner, Sparrow, & Winerman, 2004). Thus, it seems that the relation between action and outcome does not play a role in the effect of causal inferences on self-agency experiences, thereby challenging the role of causal knowledge about the relation between action and outcome in the establishment of self-agency experiences.

However, whereas people may experience agency over outcomes that they do not intend to produce or actually control, it could be questioned whether outcome priming always increases the experience of self-agency or whether there are boundary conditions to this effect. One such boundary condition may occur when one has learned that one's action has no causal relation with the outcome. After all, under normal circumstances, it would be odd to experience your own action to be the cause of an outcome when knowing from experience that the action cannot have caused the outcome (e.g., when pushing the ENTER-button is followed by rainfall). Thus, when one has learned that one's action is causally related to the specific outcome, both motor predictions and cognitive inferences contribute to experiences of self-agency. However, learning that one's action is not causally related to the outcome reduces the role of predictive and inferential processes in the emergence of self-agency experiences (cf. Synofzik et al., 2008).

Suggestive evidence for this idea comes from a recent study that examined the combined effect of motor predictions and cognitive inferences on experienced self-agency (Sato, 2009). In this study, participants pressed a left or a right key to produce two different outcomes (a blue or a red circle presented on the computer screen). These two outcomes could be produced by the participant or by the computer. Prior to observing an outcome, a consistent (i.e., same color), neutral (i.e., a color unrelated word), or inconsistent (i.e., other color) outcome representation was primed. Causal knowledge of action–outcome relations was manipulated by varying the probability of the relation between actions and outcomes. That is, each of the two responses produced one particular color in 50% (no causal relation) or 75% (causal relation) of trials. Apart from a general motor predictability effect, results showed that priming consistent outcomes only enhanced experienced self-agency (relative to priming neutral outcomes) when actions and outcomes were causally related (75%). This inferential priming effect disappeared when there was no causal relation between actions and outcomes (50%). These findings suggest that self-agency experiences followed from inferential processes only when participants learned that their actions were causally related to the outcomes, thus revealing a boundary condition of causal knowledge for outcome priming effects on experiences of self-agency.

In contrast to these findings, however, previous research has found inference effects of outcome priming on self-agency experiences in contexts where causal knowledge about action–outcome relations was absent (e.g., Aarts, Custers, & Marien, 2009; Aarts et al., 2005; Wegner & Wheatley, 1999). Clearly, in these situations the sense of agency cannot be derived from motor predictability processes. However, the fact that outcome priming augments the sense of agency in the absence of causal knowledge about the relation between action and outcomes suggests that it is important to understand when exactly causal knowledge forms a boundary condition for inferential processes to take place.

Specifically, what seems to matter is whether people have acquired knowledge about causal relations between actions and outcomes that is relevant for assessing whether one's action may have caused the primed outcome. People are less likely to experience self-agency over primed outcomes when they know there is no causal relationship between these outcomes and the actions they perform (Sato, 2009). However, people may still infer self-agency over primed outcomes when they have no relevant knowledge regarding the specific causal relation between their actions and following outcomes (e.g., when no or irrelevant action–outcome relations are learned). This concurs with everyday experiences suggesting that people can have a sense of self-agency over novel outcomes that result from their actions. The experiment reported below examined this crucial role of the presence of relevant causal knowledge about the relation between specific actions and outcomes in motor-predictive and cognitive inferential effects on experiences of self-agency.

## 2. Present experiment

In the experiment, we first manipulated knowledge about the causal relation between actions and outcomes in a probability learning task. We then measured online self-agency experiences in a subsequent action–outcome task recently employed in research studying priming effects on self-agency experiences in a context where causation is ambiguous (Aarts et al., 2009; van der Weiden, Aarts, & Ruys, 2010).

In the agency task, participants stop a rapidly presented sequence of letter strings that ostensibly masks the alternation of two words ('glass' and 'book'), by pressing a left or a right key. In actuality no words are presented. Participants then observe that the sequence stops on one of the two words (cf. a gamble machine, in which one stops rapidly rolling symbols by pushing a button), and are told that they or the computer could have determined the stopped word. Participants are briefly presented with the corresponding word or not just before they stop the sequence, observe the stopped word and indicate experienced self-agency over stopping this word.

Crucially, before the self-agency task, participants first perform a probability learning task in which pressing a left or a right key is followed by one of two words. In two conditions, the words that followed participants' actions were the same words as used in the subsequent agency-task. We therefore refer to these conditions as the agency-relevant conditions. It is important to note that in both of these conditions, participants acquired knowledge about the causal relation between the actions they performed and the outcomes that followed in the agency-task. More specifically, in one condition there was a causal relation between the actions and outcomes (80% probability of co-occurrence), while in the other condition there was no causal relation between actions and outcomes (50% probability of co-occurrence). Additionally, we introduced a control condition in which participants did not gain causal knowledge about the relation between the actions they performed and the outcome words that were used in the subsequent agency-task. Instead, participants learn that pressing a left or a right key leads to two other words ('soap' and 'chalk') with 50% probability. Thus, in this condition the knowledge that their actions and outcomes are not causally related is irrelevant to the action–outcomes in the agency-task (agency-irrelevant condition). This allowed us to assess the importance of the presence of relevant causal knowledge in prediction and inference effects on experienced self-agency. Furthermore, the control condition allowed us to separate the contribution of motor predictability and inferential priming effects in experiences of self-agency.

We expected that motor predictability and outcome priming both enhance experienced self-agency over action–outcomes. Furthermore, in line with previous work (Sato, 2009) we expected outcome priming to augment experienced self-agency when participants learned that there was a causal relation between actions and outcomes (80% agency-relevant condition), but not when participants learned there was no causal relation between actions and outcomes (50% agency-relevant condition). Importantly, if a non-causal relation is learned regarding irrelevant action–outcomes, and hence this knowledge is irrelevant for the outcomes of the self-agency task, then outcome priming effects should reemerge in the 50% agency-irrelevant condition. That is, in the 50% agency-irrelevant condition participants have no prior knowledge about the specific causal relation between the actions they perform and the outcomes that follow in the agency task and therefore the motor predictive effects should not occur while the inferential effects of outcome priming should still show up.

## 3. Method

### 3.1. Participants and design

One-hundred-and-seven undergraduates participated in return for course credit or a small fee. In the self-agency task all participants were presented with two types of trials: trials in which the outcome representation (the word that would be presented after the key press) was primed and control trials without such primes. Knowledge about the causal relation between actions and outcomes was manipulated as a between-participant factor with three levels (80% agency-relevant, 50% agency-relevant, 50% agency-irrelevant).

### 3.2. Experimental task and procedure

Participants were seated behind a computer and worked individually. After some introductions and practice with the self-agency task they moved on to two consecutive tasks: a probability learning task and a self-agency task.

#### 3.2.1. Probability learning task

The experiment started with the probability learning task. In this task, participants repeatedly pressed a left or a right key in response to an arrow that pointed to the left or the right, and monitored how often the object words 'book' or 'glass' (or 'soap' or 'chalk' in the 50% agency-irrelevant condition) would follow (for similar probability manipulations, see Chatlosh, Neunaber, & Wasserman, 1985; Moore, Lagnado, et al., 2009). The objects were pre-tested to be neutral to our sample of participants. In the 80% agency-relevant condition, participants learned that a specific action was more likely to produce a specific outcome. For example, pressing a left key produced 'book' with 80% probability and 'glass' with 20% probability, whereas pressing a right key produced 'glass' with 80% probability and 'book' with 20% probability (this relation was counterbalanced between subjects). In the 50% agency-relevant condition, participants learned that both actions produced the objects 'book' and 'glass' with 50% probability. In the 50% agency-irrelevant condition, participants learned that their actions produced the objects 'soap' and 'chalk' with 50% probability.

#### 3.2.2. Self-agency task

Next, participants performed the self-agency task. They were told that this task was designed to examine experiences of self-causation when causation is ambiguous. For this purpose, they learned to stop a sequence of letter strings, rapidly presented in the middle of the computer screen, by pressing a left or a right key. Each trial started with a warning signal (i.e., 'pay attention' presented for 500 ms.), followed by the alternation of letter strings, and at some point, the stop-cue (an arrow pointing to the left or the right). After each stop, an object word would appear ('glass' or 'book'). Thus, for participants in the agency-relevant conditions, the object words were the same objects that followed their left and right key presses in the probability learning task. For participants in the agency-irrelevant control condition, the objects were new. Participants were told that the presented object could also be determined by the computer. Participants were thus led to believe that either they themselves or the computer could be the cause of the presented object. In actuality, the computer always determined the presented product.

In each trial, 20 letter strings were presented for 150 ms with a 30-ms interval between two successive strings. Participants were told that the two object words were briefly presented in between the different strings of capital letters (e.g., PAEXJD), so that they would not be able to see the object words. In actuality, as default a row of neutral *Xs* was presented during this interval. Only in prime trials, the object on which the sequence would stop was primed (in capital letters) for seven times in a row, starting after the presentation of the first five letter strings (i.e., after 870 ms.) and subsequently once every other interval. Thus, the letter strings served as pre- and post-masks for the primes, and the time between primes was 330 ms. The time between the last prime and the STOP-cue was 510 ms.

In line with earlier research that studied outcome priming effects on experienced self-agency (e.g., Aarts et al., 2009; Sato, 2009; van der Weiden et al., 2010), we presented the primes briefly (30 ms) to prevent participants from becoming aware of the potential role of the outcome primes in changing their experiences of self-agency (see e.g., Aarts et al., 2009; for a subliminality check on this procedure). After participants pressed the stop key, the object word was presented and remained on

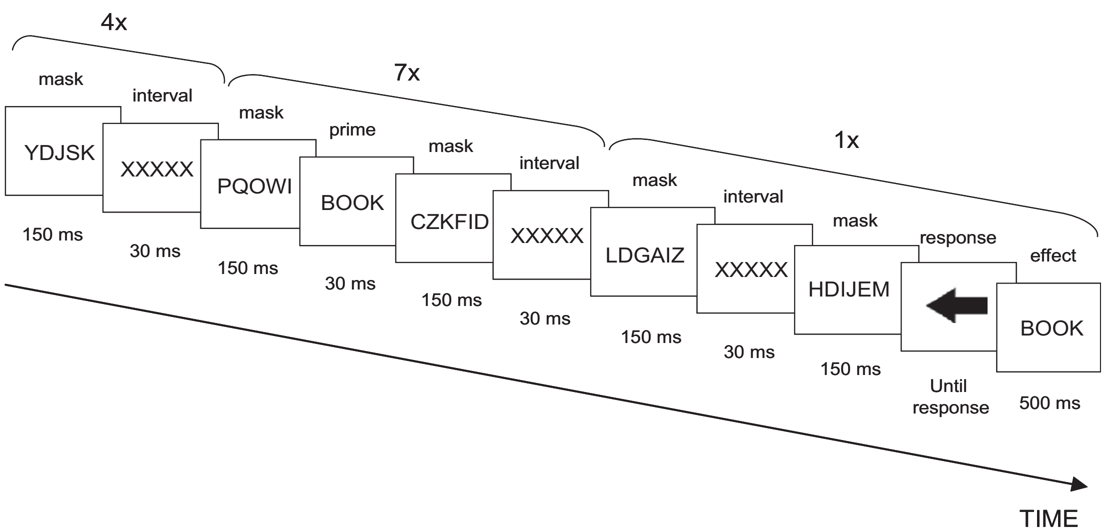


**Fig. 1.** Schematic example of a prime trial in the agency-task.

**Table 1**
Overview of number and type of trials in the agency-task, and their relation to the learned action–outcome probabilities for the different conditions. The relations between actions and outcomes were counterbalanced between subjects.

| | Probability learning task | | | Agency-task | | | |
|---|---|---|---|---|---|---|---|
| | Action | Outcome | Probability | Action | Outcome | Total trials | Primed trials |
| 80% relevant | Left | Book | 80% | Left | Book | 8 | 4 |
| | Right | Glass | 80% | Right | Glass | 8 | 4 |
| 50% relevant | Left | Book | 50% | Left | Book | 8 | 4 |
| | Right | Glass | 50% | Right | Glass | 8 | 4 |
| 50% irrelevant | Left | Soap | 50% | Left | Book | 8 | 4 |
| | Right | Chalk | 50% | Right | Glass | 8 | 4 |

the screen for 500 ms (see also Fig. 1 for a schematic example of a trial sequence for prime trials). At the end of each trial participants indicated to what extent they felt that they had stopped the sequence on the presented object (e.g., Aarts et al., 2005; Sato & Yasuda, 2005). This agency feeling was measured on a 10-point scale [*not at all me* (0) – *absolutely me* (9)].

Each of the two object words was presented as an outcome 16 times—8 times after a left key press and 8 times after a right key press (note that the probability that 'book' or 'glass' followed a left or a right key press in this agency-task was 50%). The task thus consisted of 32 trials. Half of these trials were filler-trials to ensure that all combinations of actions and outcomes occurred. The 16 trials of interest (those trials pertaining to the 80% probability action–outcome relations) consisted of eight prime trials and eight no-prime trials (see Table 1 for an overview of the number and type of trials in the agency-task and their relation to the learned action–outcome probabilities for the different knowledge conditions). Trials were presented randomly.

In line with earlier work (Aarts et al., 2009; van der Weiden et al., 2010), debriefing showed that none of the participants reported to have seen the primes. Furthermore, none of them realized the true nature of the study.

## 4. Results

Average self-agency ratings were computed for the no-prime trials and the prime trials. These ratings were subjected to an ANOVA, with priming condition (no-prime vs. prime) as a within participant variable and causal knowledge as a between participant variable. This analysis revealed a main effect of causal knowledge ($F(2, 105) = 3.83$, $p = .03$, $\eta_p^2 = .07$), such that agency-ratings were higher when learned action–outcome probabilities were 80% ($M_{agency\text{-}related} = 4.92$, $SD = 1.89$), rather than 50% ($M_{agency\text{-}related} = 3.48$, $SD = 2.55$; $M_{agency\text{-}unrelated} = 3.55$, $SD = 2.55$). Comparing the mean of the 80% condition with the combined means of the 50% conditions in a separate contrast analysis also yielded a reliable effect ($F(1, 104) = 7.72$, $p = .006$, $\eta_p^2 = .07$), indicating that knowledge about the causal relations between actions and outcomes was learned according to the different probability patterns. Furthermore, there was a main effect of priming ($F(1, 106) = 5.31$, $p = .02$, $\eta_p^2 = .05$). Replicating previous work (e.g., Aarts et al., 2005; Wegner & Wheatley, 1999), self-agency feelings were higher for prime trials ($M = 4.02$, $SD = 2.49$) compared to no-prime trials ($M = 3.83$, $SD = 2.47$). Importantly, and in line with our hypothesis, the expected interaction between priming and causal knowledge emerged ($F(2, 105) = 3.66$, $p = .03$, $\eta_p^2 = .07$).

In order to test our specific hypotheses, we performed simple effect analyses. As expected, results showed that outcome priming only enhanced experienced self-agency in the 80% agency-relevant ($F(1, 104) = 5.55$, $p = .02$, $\eta_p^2 = .05$) and 50% agency-irrelevant conditions ($F(1, 104) = 6.47$, $p < .02$, $\eta_p^2 = .06$), and not in the 50% agency-relevant condition ($F < 1$). Fig. 2 presents mean experienced self-agency for each cell in the design.

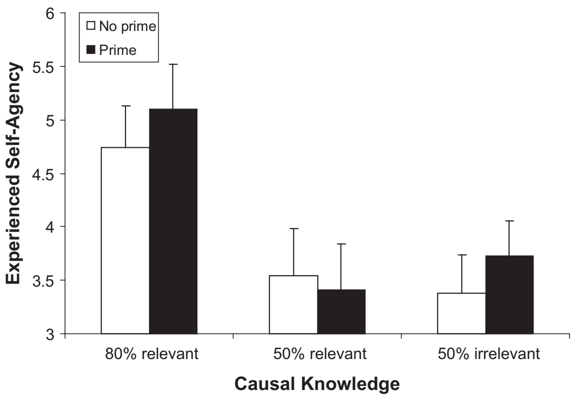


**Fig. 2.** Experienced self-agency as a function of outcome priming (no vs. yes) and causal knowledge (80% agency relevant vs. 50% agency relevant vs. 50% agency irrelevant). Error bars represent standard errors of the means.

## 5. General discussion

The present study examined the role of causal knowledge about action–outcome relations in the contribution of motor-predictions and cognitive inferences to experiences of self-agency over action–outcomes. Results showed that both predictive effects of learned action–outcome probability and inferential effects of outcome priming enhanced experienced self-agency. Furthermore, we established that causal knowledge about the relation between specific actions and outcomes moderated the contribution of both predictions and inferences to experiences of self-agency. When participants learned that actions and outcomes were causally related (with a probability of 80%), motor predictability and outcome priming both enhanced self-agency experiences compared to participants who learned that actions and outcomes were not causally related (with a probability of 50%). Importantly, when participants learned that there was no causal relation between actions and outcomes that were irrelevant to the outcomes over which self-agency was assessed, motor prediction effects stayed off while outcome priming effects re-emerged.

These findings replicate and extend previous work (Sato, 2009) on the role of motor predictions and cognitive inferences in the emergence of self-agency experiences, by showing that outcome priming effects on self-agency crucially depend on whether one has acquired relevant knowledge that informs one that one's actions and outcomes are not causally related. That is, if one has acquired knowledge that one's actions are not causally related to the agency-relevant outcomes then motor predictions and cognitive inferences do not influence self-agency. However, if one has learned that irrelevant outcomes are not causally related to one's actions, and hence one has learned no relevant knowledge concerning the agency-relevant outcomes, then motor prediction effects do not occur but inferential priming effects do. These findings suggest that people can experience self-agency over novel action–outcomes, as long as they have no prior relevant information about the causal relation between the specific action and outcome.

We further showed that when actions and outcomes were learned to be causally related, predictions and inferences independently affected experiences of self-agency. The independent contribution of motor predictability and cognitive inferential effects of outcome priming has also been addressed in research on the sense of agency in operant action, assessed by the so-called intentional binding effect. Whereas intentional binding was originally suggested to rely only on sensory-motor prediction processes that accompany our intentional actions, recent work suggests that intentional binding is also sensitive to inferential effects of outcome priming. Specifically, when people perform an involuntary induced action in which there are no motor prediction processes involved (e.g., pressing a key triggered by an external device) and this action is followed by an outcome (e.g., a tone), intentional binding, and hence sense of agency is enhanced by outcome priming (Moore, Haggard, & Wegner, 2009). Given that intentional binding represents an implicit measure of self-agency, and seems to be related with our explicit measure of authorship ascription (Ebert & Wegner, 2010), the present findings suggest that these priming effects in intentional binding of involuntary action are constrained by the causal knowledge that people have about the relation between action and outcome.

The present finding that outcome priming effects on experienced self-agency vanish when people learn that their action and the outcome are not causally related raises questions as to how such causal knowledge reduces the impact of inferential processes in experiences of self-agency. One possibility is that people no longer represent their action in terms of a specific outcome when they learn that the action is not causally related to the given outcome. Recent research shows that outcome priming effects on experiences of self-agency are less pronounced when people do not represent their behavior in terms of why (i.e. outcome) they perform an action (van der Weiden et al., 2010). Thus, differences in representing behavior may underlie the moderating role of causal knowledge in inferential priming effects on experienced self-agency. Another possibility concerns the idea that people may establish different beliefs as a result of learned causal knowledge. For instance, people may form the belief that they cannot control the given outcome by performing a certain action when they learned that that action is not causally related to that outcome, thus discouraging them to infer self-causation over the specific action–outcome. Consistent with this notion, a recent study (Desantis, Roussel, & Waszak, 2011) indicates that the sense of agency (assessed in the intentional binding task) is affected to a lesser extent when people believe they do not cause the outcome. Whether differences in behavior representation or causal belief account for the present findings remains an empirical question.

Importantly, however, based on the present findings we shed new light on the combined contribution of motor predictions and cognitive inferences on self-agency experiences. More specifically, we demonstrated that causal knowledge about actions and outcomes plays a crucial role in both motor-predictive and cognitive inferential effects on experienced self-agency. These two effects operate independently: People experience self-agency over action–outcomes when their motor control system predicts the occurrence of the outcome and when the outcome corresponds with the outcome they had in mind. However, when one learns that the outcome at hand does not causally follow from one's own action, and this knowledge is relevant for subsequent authorship processing, experiences of self-agency are not affected by motor predictability or inferences based on outcome priming. To conclude, our findings indicate that the experience of self-agency cannot be deceived by the mere priming of outcomes when people know that there is no causal relation between the actions they perform and the outcomes that follow.

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