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The one exception: The impact of statistical regularities on explicit sense of agency

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Abstract

Establishing causal beliefs by observing regularities between actions and events in the environment is a crucial part of goal-directed behavior. Sense of agency (SoA) describes the corresponding experience of generating and controlling actions and subsequent events. Investigating how SoA adapts to situational changes in action-effect contingency, we observed even singular disturbances of perfect action-effect contingencies to yield a striking impact on SoA formation. Moreover, we additionally included disturbances of regularity that are not directly linked to one's own actions. Doing so allowed us to investigate how SoA might be a concept that goes beyond own actions towards a more generalized, subjective representation of control regarding environmental events. Indeed, the present experiments establish that, while SoA is highly tuned toward action-effect relations, it is also sensitive to events that occur without one's own action contribution. SoA thus appears to be exceptionally sensitive to singular breakpoints of perfect control with agents disproportionally incorporating such events during SoA formation while at the same time building on a rich situation model.

Keywords

sense of agency; control; action-effect contingencies; statistical regularity; odd ball

Public Significance Statement

Sense of agency (SoA) as the subjective experience of control over our actions and their effects, is thought to be an integral and influential part of action decisions and action execution. To understand its formation in human agents, we need to understand how this subjective experience of control relates to actual environmental regularities, i.e., the agent's objective control. Our results show that SoA is highly sensitive to environmental regularities, both directly and not directly linked to own actions, demonstrating that SoA is a concept that goes beyond own actions. Importantly, our results suggest that already singular instances of regularity disruption trigger strong reductions in explicit SoA. Altogether, our data showcase that while subjective experience of control is strongly influenced by actual control, both deviate in crucial aspects, and thus have to be distinguished in experimental procedure and terminology.

1. The impact of statistical regularities on explicit sense of agency

Perceived or inferred causality between events represents a cornerstone of an individual's understanding of his or her environment. For example, if a certain action is likely to be followed by a specific event, this co-occurring increases the individual's belief about causal effectiveness in producing a desired change (Rescorla & Wagner, 1972; Rochat & Striano, 1999; Shanks & Dickinson, 1991; Watson, 1985). Such statistical regularities between actions and consequences play a crucial role in motivating future actions and in guiding individuals toward achieving goals (Behrens et al., 2007; Eitam et al., 2013; Elsner & Hommel, 2004; Karsh et al., 2016; Penton et al., 2018; Reis et al., 2023). Importantly, this belief about the effectiveness of own actions in the surrounding world invokes the subjective experience of authorship and responsibility for the perceived changes (Moore, 2016; Moore & Fletcher, 2012; Schwarz et al., 2023), i.e., sense of agency (SoA, Haggard & Tsakiris, 2009). In other words, SoA refers to both the feeling of being in control of one's executed actions and the feeling of being in control of effects observable in the environment. Theories assume that SoA evolves when events happen according to an agent's prior intention (theory of apparent mental causation, Moore, 2016; Wegner, 2004; Wegner & Wheatley, 1999) or when motor-related predictions generate little prediction error (internal forward model, Jeannerod, 2009; Wolpert & Miall, 1996). In case of a mismatch, the event is seen as externally produced and SoA can be diminished or even lost (Moore, 2016; Moore & Fletcher, 2012). Thus, contingency, i.e., the frequent, and hence predictable, covariation of action and event supports action-effect learning and is thought to promote feelings of authorship and perceived control (Moore et al., 2009).

Indeed, many studies corroborate that manipulating contingency affects SoA (e.g., Majchrowicz & Wierzchoń, 2018; Metcalfe et al., 2013; Schwarz et al., 2022; van der Weiden et al., 2011) with an increased likelihood of the critical event following an action generally bolstering an agent's SoA over the event (Castegnetti et al., 2020; van der Weiden et al., 2011). For instance, SoA decreased significantly when action-effect contingency dropped from 100% to 75% (Metcalfe et al., 2013). Our own previous work lends further support for these findings: Here, action-effect contingency was manipulated to include 5 different contingency levels, namely a 50%, 70%, 80%, 90%, and 100% condition, thereby representing a dynamic and varied environment with different contextual properties (Schwarz et al., 2022). In these five conditions, the certainty of the outcome, i.e., the likelihood of a contingent and thus expected effect following an action, was varied. Results indicated that higher action-related contingency increased perceived control as a marker for SoA. Specifically, agency summary scores, i.e., agency ratings that summarize the participants' agency experience across the experienced trials, both contingent and non-contingent, within a given experimental block, showed a quadratic relation of contingency and SoA. That is, while the 100% contingency condition resulted in maximum control, the near-perfect 90% contingency condition already showed a marked loss in perceived control. In contrast, changes in action-effect contingency affected perceived control to a lesser degree for higher uncertainty levels, i.e., 50% and 70% conditions. This over-consideration of near-perfect action-effect contingencies suggests that participants were highly sensitive to rare violations. Thus, manipulating the learnt causal relation between a certain motor action and its specific consequence in the environment led to significant alterations in agentic experience.

Nevertheless, our theoretical understanding of SoA formation in dynamic environments is still in its infancy. Such environments are commonplace in everyday life, however. This includes situations in which actions lead to certain events (as studied in the work reviewed above), but also situations in which events occur without involvement of the observer (Hubbard, 2013; Watson, 1997), and both of these scenarios can contribute to the agent's predominant model of the situation (Schneider et al., 2020). Indeed, previous evidence suggests that environmental stimuli that are not acted upon may influence SoA (Hon et al., 2018). Considering SoA as a subjective counterpart to action-event probabilities encountered in the environment, therefore, calls for viewing the relation of SoA and contingency in a more generalized manner including instances of events that are not directly linked to one's own actions (Schwarz et al., 2022). This degree of contingency (Delta-*p*) can be expressed as the formula $\Delta p = p(E|A) - p(E|\neg A)$, and is therefore not only defined by the probability of an expected event (E) occurring after performing an action (A), but also by the probability of an event (E) occurring even though no specific action (¬A) was performed beforehand (Rescorla, 1967; Watson, 1997). Indeed, when investigating action-effect learning, action-event relations seem to be learnt best when the overall frequency of an expected event p(E|A) is high and when p(E|¬A) is low, i.e., the expected event only rarely occurred in the absence of a prior action (Elsner & Hommel, 2004).

But how is SoA as the judgment of being responsible for causing actions or effects affected by events that occur without one's own contribution? In such cases, individuals should attribute such events in the environment as being caused by external factors and not by themselves. If SoA serves as a subjective counterpart to action-event probabilities encountered in the environment, both the action-related contingency p(E|A) and the general statistical regularity p(E|¬A) should affect SoA formation (Schwarz et al., 2022). If SoA only pertains to own actions and their direct consequences, SoA formation should not be particularly sensitive to other events clearly occurring without one's own contribution, irrespective of their identity (i.e., the actual source generating the event).

Moreover, we have to ask: How sensitive is SoA formation to singular disturbances of perfect regularity? That is, how much irregularity, action-related or otherwise, is necessary for a significant impact on SoA formation? As stated earlier, SoA seems to be informed by processes relevant to action-effect learning. One critical aspect when forming associations between events in action-effect learning is the inclusion of prediction errors (Jeannerod, 2009; Sato & Yasuda, 2005; Villa et al., 2020). If SoA simply reflects the prevalent environmental regularities, SoA should systematically increase with increasing environmental regularity. If SoA is related to learning processes, we might expect even singular disruptions to have substantial impact if agents expect perfect action-effect contingencies (Rescorla & Wagner, 1972). Surprising prediction errors, triggered by events that occur unexpectedly and rarely (i.e., oddballs), draw immediate attention (Berti & Schröger, 2001; Duncan-Johnson & Donchin, 1977; Polich, 2007) and trigger corresponding adjustments in cognitive processing (Holland & Schiffino, 2016; Melcher et al., 2015; Notebaert et al., 2009). Thus, experiencing only few irregularities in action-event associations may already lead to reduced SoA, as such instances of violated event predictions may be processed particularly strongly (Burns et al., 2010).

In the present series of experiments, we thus extend previous theorizing by characterizing how an agent's SoA formation is affected by singular disturbances of perfect action-effect contingencies. Moreover, we additionally included disturbances of regularity that are not directly linked to one's own actions and, thus, investigate how SoA might go beyond one's own actions towards a more generalized, subjective representation of control regarding environmental events. To this end, we adapted our previous task in which participants were asked to press one of two possible keys to elicit a smiling face (Schwarz et al., 2022). To assess SoA, participants were asked to integrate and summarize their experiences from various situations by indicating their perceived control over the appearance of the smiling face. This evaluation of SoA allows for the integration of trials with different levels of perceived control into one metacognitive judgment of perceived SoA in a specific dynamic situation, including retrospective reflections about control in the whole block of trials (Synofzik et al., 2008). Summary evaluations of SoA were chosen to explore event probabilities impacting the stable sense of agency established over time (Behrens et al., 2007). Explicit ratings can, of course, be potentially subject to individual biases independent of sense of agency. However, given the present state of literature, explicit ratings are currently still the most reliable measure for sense of control in our view, and thus preferable to other methods (see Limitations paragraph in the General Discussion section for details). In the first experiment, we tested whether a wide range of variations in general statistical regularity without a direct action-effect relation (i.e., the occurrence of events without prior actions) would affect explicit SoA summary judgments. Experiment 2, then, contrasted the separate influences of the two probabilities of the Delta-*p* formula on summary evaluations of SoA in modified conditions of high range regularities in which only singular irregular situations disrupted perfect regularity.

2. Experiment 1: Statistical regularities and SoA

In Experiment 1, we varied the probability p(E|¬A) of smiling faces appearing without a prior action in a wide range of conditions (50%, 70%, 80%, 90% and 100%). Accordingly, contrary to our previous study (Schwarz et al., 2022), the first half of the contingency formula, i.e., p(E|A), was held constant. We expected SoA to dynamically adapt to situational changes in general statistical regularity, even without own contribution to the occurrence of perceived events. Additionally, we tested if SoA is most sensitive to regularities pertaining to one's own actions, i.e., to variations in action-related contingency, by combining the data of Experiment 1 with the data of our previous study (Schwarz et al., 2022). The existing literature depicts SoA as strongly associated with conducting voluntary, intentional, and free actions (Moore, 2016; Wegner & Wheatley, 1999), emphasizing the tight link of self-generated motor activity and its predictions about sensory consequences in the environment (Blakemore et al, 1999; Haggard et al., 2002; Moore & Haggard, 2008; Weller et al., 2020). Hence, people should experience a strong reduction in SoA when a prior voluntarily conducted action leads to an unexpected consequence. Likewise, in situations in which participants did not form a specific intention about (not) acting, SoA should be reduced. In contrast, deliberately withholding an action in order to make an event occur can indeed be expected to yield SoA (Weller et al., 2020). Accordingly, effect binding can also occur for intended non-actions and its effects (Kühn et al., 2009; Weller et al., 2017). Thus, SoA can reliably be elicited for actions (and their predicted consequences) as well as for deliberate non-actions (and their predicted consequences), although the latter to a somewhat lesser degree (Weller et al., 2020). Correspondingly, we expect SoA to be most sensitive to action-related contingency, but to also reflect general statistical regularity with no action link to a smaller degree, particularly when there was a clear intent to not act in any way. This would represent a conceptualization of SoA that focuses primarily on own actions, but that also accounts for general statistical regularities of the environment beyond one's own actions.

2.1. Methods

The preregistration, data, and analyses files are available on the Open Science Framework (https://osf.io/9zpme and https://osf.io/cv24n).

2.1.1. Participants. 101 participants were recruited via Prolific in the spring of 2022. This sample size was based on an a priori power calculation, ensuring a power of $1-\beta = .8$ with an $\alpha = .05$ to detect an effect size of $r = .3$ (pwr package in R). Our previous study (Schwarz et al., 2022) showed very strong effects of contingency on SoA ratings. However, as we expect the impact of our manipulation in this study to be more subtle than in the previous study, we chose to lower the expected effect sizes to medium sized effects to account for this difference in experimental manipulation and still ensure enough power to detect potential differences in our dependent variables. Additionally, accounting for possible drop-outs, we added an extra 20% of participants. Of these participants, 15 (14.9%) were excluded, 1 of them due to technical problems in recording reaction times and 14 others due to their answers in a post-experimental questionnaire in which they stated to have had serious language (*n* = 1) or instruction comprehension (*n* = 2) difficulties, to have not concentrated properly on the study (*n* = 2), to have not answered the ratings truthfully (*n* = 4), to have not followed instructions (*n* = 1), or to have guessed the correct purpose of the study (*n* = 1). These exclusion criteria were already predetermined in the preregistration. In addition, one criterion was added later, i.e., the subjective estimation of having pressed a key in more than 30 trials (22.7%) during passive trials even though in these trials participants were explicitly instructed not to do so (further exclusion of *n* = 3). Detailed results concerning the post-experimental questionnaire can be found in Table S5 in the Supplementary Material.

The remaining sample size of *N* = 86 retained a power of 1-β = .81. Mean age of this adjusted sample was 26.7 years (*SD* = 8.9, range 18 - 62) with 46 participants identifying as male, 39 as female and 1 as non-binary. 80 participants reported being right-handed and 5 participants reported being left-handed (1 person did not answer this question). Participants reported a total of 17 nationalities, the most frequently mentioned countries being Portugal (*n* = 18), Poland (*n* = 17), Mexico (*n* = 11) and South Africa (*n* = 9). Participants gave informed consent prior to the experiment and received monetary compensation.

2.1.2. Apparatus. The experiment was set up to run in the browser of the participants' home computer using the JavaScript engine lab.js (Henninger et al., 2022). The program was provided to the participants via a private server. This setup, therefore, included variable viewing distance and stimulus size across participants. Presentation of all stimuli was centered on a white background and scaled according to the display resolution. The only requirement for successful participation was to use a desktop computer or laptop with physical keyboard and mouse/trackpad.

2.1.3. Design and Procedure. The procedure of Experiment 1 closely followed our previous study on the impact of action-related contingencies during SoA formation for optimal comparison purposes (Schwarz et al., 2022). Participants first received instructions asking them to produce as many smiling faces as possible during the experimental blocks by pressing either the A or L key with their left or right index finger, respectively. Only one key was effective in producing the smiling emoticon in each block, and the effective key was randomized across blocks. Participants were encouraged to only press a key when they were explicitly asked to do so, to concentrate, and to respond quickly, although there was no time limit in the individual trials.

Altogether, the experiment consisted of 10 experimental blocks of 60 experimental trials each, with 10 additional practice trials provided at the start of each block to familiarize participants with the task and the mapping of keypress and subsequent event. As a main measure, twice per block (halfway through, i.e., after 30 trials, and at the end, i.e., after another 30 trials), participants were asked to rate their perceived control over the appearance of the face (“How much control did you feel over the appearance of the face [during the current block (1st block half) / since the last rating (2nd block half)]?”) as a marker for SoA and their perceived predictability of the appearance of the face (“How predictable was the appearance of the face to you [during the current block (1st block half) / since the last rating (2nd block half)]?”). The rating scales ranged from 0 (no control / not predictable) to 100 (full control / completely predictable), resulting in summary scores of control and predictability that allowed participants to aggregate their experiences from various trials to form an overall judgment.

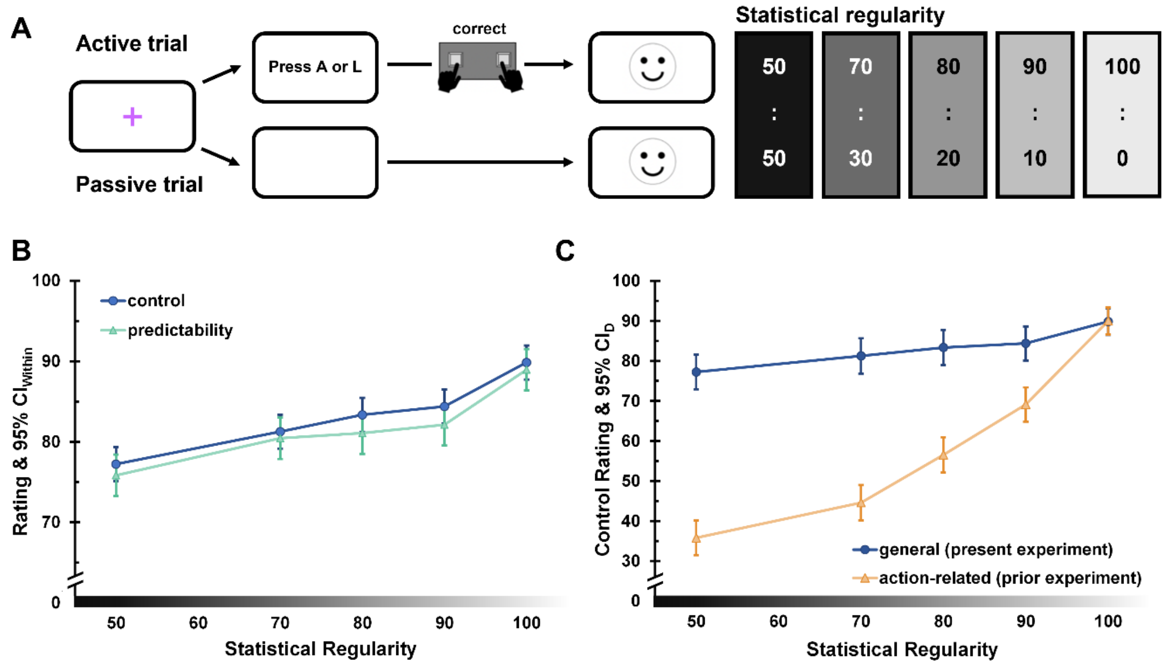
All trials (see Fig. 1A for an overview) started with a fixation cross displayed for 300 ms. In active trials, participants were then prompted to press one of two keys (“Press A or L”). Successful keypresses according to the current mapping made a smiling emoticon appear for 400 ms. Pressing the wrong key did not produce an emoticon but rather a blank screen for 400 ms. The next trial started after a 600 ms intertrial interval. In passive trials, by contrast, participants were not asked to press any key. The smiling emoticon still appeared after a 300 ms pause so that each passive trial included an experience of the event without involvement of one’s own action. Identical to active trials, passive trials ended on a 600 ms intertrial interval.

Blocks differed in their ratio of active trials to passive trials, i.e., in the probability $p(E|\neg A)$ of smiling faces appearing without conducting a prior action: This statistical regularity was manipulated to include 5 different levels (50%, 70%, 80%, 90% and 100% active trials). For instance, for the 90% regularity level each block half consisted of 27 active (or regular) trials and 3 (i.e., 10%) passive (or irregular) trials. Passive trials and active trials were randomly interspersed. Over the course of the experiment, each statistical regularity level was featured twice, resulting in 10 blocks that were presented in randomized order.

After completing the experimental blocks, participants were asked about their performance regarding effort, paid attention and language and comprehension problems. It was clearly indicated that negative responses to any of these questions would not have consequences of any kind for the participants.

Figure 1

Study design and main results of Experiment 1



Note. (A) Study design of Experiment 1 in which participants were either confronted with active trials or passive trials. In active trials (or regular trials), a prompt asked participants to press a key (either a A or L, participants could freely choose). Pressing the key associated with the effect (i.e., the correct key) triggered a smiling face. In passive trials (or irregular trials), the event (smiling face) appeared automatically after a short delay without any prior keypress. Participants experienced five different regularity levels (50%, 70%, 80%, 90%, or 100%) with higher regularity including correspondingly more active trials and fewer passive trials. (B) Mean control and predictability ratings for different regularity levels. Error bars depict 95% within-subjects confidence intervals ($\mathrm{CI}_{\mathrm{Within}}$, Loftus & Masson, 1994). (C) Differences in control ratings between our prior study (Schwarz et al., 2022) with manipulations in action-related statistical regularity (p(E|A)), and the present experiment with manipulations in general statistical regularity with no direct action link (p(E|¬A)). Control ratings were higher for manipulations of general statistical regularity without direct action link, with differences getting smaller as probabilities of regular trials increased. Error bars depict 95% confidence intervals of the between-subjects difference (CI_{D}) between control ratings in the prior and present experiment for each regularity level (Pfister & Janczyk, 2013).

2.1.4. Data Analysis. For all data analyses, we excluded the 10 practice trials at the beginning of each block. For the remaining experimental trials, we conducted repeated-measures analyses of variance (rmANOVAs) with the within-subjects factor *Regularity Level* (50% vs. 70% vs. 80% vs. 90% vs. 100%) separately for each dependent variable (control and predictability rating). We employed two-tailed paired *t*-tests as follow-up tests for pairwise comparisons with corresponding effect sizes calculated as $d_z = \frac{t}{\sqrt{n}}$. To evaluate the relationship between control and predictability ratings, we implemented the within-subjects factor *Rating* (control vs. predictability) in the aforementioned rmANOVA. Data from the prior experiment[1] (Schwarz et al., 2022) were included in mixed-design ANOVAs with the between-subjects factor *Experiment* (prior vs. present) and the within-subjects factor *Regularity Level* (50% vs. 70% vs. 80% vs. 90% vs 100%) for each dependent variable (control and predictability rating) to investigate if action-related statistical regularity in the prior experiment or general statistical regularity (with no direct action link) in the present experiment impacted perceived control and predictability differently. For pairwise comparisons of rating scores between experiments we employed follow-up *t*-tests plus effect sizes *d* for independent samples.

As a converging set of analyses, we fitted mixed-effects models for control ratings (lmer package, RStudio, 2020) with statistical regularity as fixed effect, and including random slopes and random intercepts (Oberauer, 2022). Linear and quadratic models, as well as marginal and conditional R^2 were tested and compared to models and explained variances of the prior experiment.

Finally, we assessed performance in terms of response times (RT) across the different regularity levels. We particularly probed for post-oddball slowing (Melcher et al., 2015; Notebaert et al., 2009) after passive (irregular, i.e., oddball) trials relative to active trials. We excluded incorrect trials as well as first trials after ratings and trials with RTs deviating more than 3 standard deviations around individual condition means. We then conducted a rmANOVA with the two within-subjects factors *Regularity Level* (50% vs. 70% vs. 80% vs. 90%) and *Preceding Trial* (active vs. passive) for the dependent variable RT (time until key was pressed in active trials). As longer RTs in trials following oddballs may be the consequence of a time-consuming orientation towards such unexpected events and a reorientation to the task (Barcelo et al., 2006; Pfister et al., 2020; Saunders & Jentzsch, 2012), this performance analysis allowed us to test the extent to which passive trials were perceived as expectancy violations leading to a delay in subsequent trials. To explore this orienting account for unexpected events further, we additionally compared mean RTs in trials after an incorrect vs. after a successful keypress for each participant using two-tailed paired *t*-tests. Post-error slowing is a widely employed cognitive control effect and describes the observation of prolonged responses after committing an error in choice tasks, which can again be seen as an

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[1] The experiment conducted by Schwarz et al. (2022) targeted the impact of action-related contingency on perceived control and perceived predictability. N = 491 completed 10 blocks as in the present experiment but action-effect contingency was manipulated as the probability p(E|A) that an expected effect (a smiling face) in comparison to an unexpected effect (a frowning face) occurred after a keypress (50%, 70%, 80%, 90% and 100% action-related contingency). Agency and predictability summary scores showed a quadratic relation of contingency and SoA, driven by a disproportionately strong impact of perfect action-effect contingencies. Explicit ratings were higher in conditions of higher contingency.

unexpected situation resulting in an orienting and readjusting response (see Notebaert et al., 2009; Pfister & Foerster, 2022).

Table 1

Mean control ratings in different regularity conditions of the present experiment (general statistical regularity with no direct action link; $M_{present}$*) and in comparison with control ratings of the prior experiment (Schwarz et al., 2022; action-related statistical regularity;* M_{prior}*)*

Regularity	$M_{present}$	Pairwise comparisons	M_{prior}	Pairwise comparisons
50%	77.24		35.78	$50\%_{prior}$ *vs.* $50\%_{present}$: *t(575)* = 18.98, *p* < .001, *d* = 2.22
70%	81.26	*50% vs. 70%: t(85)* = 3.55, *p* < .001, d_z = 0.38	44.58	$70\%_{prior}$ *vs.* $70\%_{present}$: *t(575)* = 16.45, *p* < .001, *d* = 1.92
80%	83.35	*70% vs. 80%: t(85)* = 2.23, *p* = .029, d_z = 0.24	56.53	$80\%_{prior}$ *vs.* $80\%_{present}$: *t(575)* = 11.97, *p* < .001, *d* = 1.40
90%	84.39	*80% vs. 90%: t(85)* = 1.01, *p* = .316, d_z = 0.11	69.13	$90\%_{prior}$ *vs.* $90\%_{present}$: *t(575)* = 7.05, *p* < .001, *d* = 0.82
100%	89.85	*90% vs. 100%: t(85)* = 3.77, *p* < .001, d_z = 0.41	90.01	$100\%_{prior}$ *vs.* $100\%_{present}$: *t(575)* = -0.09, *p* = .925, *d* = -0.01

2.2. Results

Fig. 1B shows mean control and predictability ratings for different regularity levels of Experiment 1 and Fig. 1C a comparison of mean control ratings of Experiment 1 with mean control ratings of our prior study (Schwarz et al., 2022).

2.2.1. Impact of statistical regularity. As expected, general statistical regularity had a strong effect on perceived control, $F(4, 340) = 24.03$, $p < .001$, $\eta_p^2 = .22$, ε = .77 (Greenhouse-Geisser (GG)-corrected). Control ratings increased with higher regularity levels, i.e., with higher probabilities of active trials (see Fig. 1B, Table 1). The steepest increase in control ratings was observed between the 90% and 100% regularity condition, $M_{present, Diff} = 5.46$, $t(85) = 3.77$, $p < .001$, $d_z = 0.41$. Predictability ratings showed a similar main effect of general statistical regularity, $F(4, 340) = 19.54$, $p < .001$, $\eta_p^2 = .19$, ε = .67 (GG-corrected). Results for pairwise comparisons between individual levels mirrored the findings for control ratings (see Table S2 in the Supplementary Material). When applying Bonferroni-correction to account for multiple comparisons in both control and predictability ratings, only the pairwise differences between the 50% and 70% condition and the 90% and 100% condition retain significance (see Tables S1 and S2 in the Supplementary Material). Consequently, the significant difference between mean control ratings in the 70% vs. 80% condition in the original analysis should be interpreted with caution. Overall, control ratings, $M_{control} = 83.2$ ($SD = 15.7$), and predictability ratings, $M_{predictability} = 81.7$ ($SD = 19.5$), did not differ significantly, $F < 1$.

2.2.2. Comparison of action-related statistical regularity (prior experiment) and general statistical regularity without a direct action link (Exp. 1). Statistical regularity affected SoA, $F(4, 2300) = 329.85$, $p < .001$, $\eta_p^2 = .37$, $\varepsilon = .87$ (GG-corrected), indicating that in both experiments higher percentages of regular trials compared to irregular trials were associated with increasing perceived control. Control ratings were generally higher when manipulating general statistical regularity (with no direct action link) compared to action-related statistical regularity, main effect *Experiment*, $F(1, 575) = 202.06$, $p < .001$, $\eta_p^2 = .26$. This effect was mainly driven by the lower statistical regularity levels, i.e., conditions which had a high percentage of irregular trials, interaction *Experiment x Regularity Level*, $F(4, 2300) = 139.96$, $p < .001$, $\eta_p^2 = .20$, $\varepsilon = .87$ (GG-corrected). That is, except for the 100% condition, $t < 1$, participants generally perceived more control in the present experiment with the largest difference between action-related and general statistical regularity occurring in the 50% condition, $M_{50\%,\text{ Diff}} = 41.46$, $t(575) = 18.98$, $p < .001$, $d = 2.22$ (see Fig. 1C, Table 1). Results did not differ when applying Bonferroni-correction (see Table S1). Predictability rating results mirror these findings (see details for the ANOVA and pairwise comparisons with and without Bonferroni-correction in Table S2 in the Supplementary Material). When regressing control ratings on action-effect contingencies (i.e., action-related statistical regularity) in the prior experiment, the best model fit was achieved by a quadratic model. No such clear preference was found in the present experiment, suggesting the linear model as the simplest fit. Now, the complete model captured 82.7% of the measured variance (conditional R^2) compared to 76.8% in the prior experiment (but please note the inclusion of a random slope in the present study instead of a random intercept as in the prior experiment to accommodate recent statistical recommendations; e.g., Oberauer, 2022). The marginal R^2 differed substantially between the prior experiment (52.3%) and the present experiment (4.8%), highlighting the differing impacts of regularity manipulations (action-related vs. no direct action link). However, including the factor general statistical regularity as a fixed effect into the model of the present experiment nevertheless significantly improved model quality, $\chi^2(1) = 40.09$, $p < .001$.[2]

2.2.3. Performance analysis. RTs were sensitive to changes in regularity, main effect *Regularity Level*, $F(3, 255) = 12.82$, $p < .001$, $\eta_p^2 = .13$, $\varepsilon = .84$ (GG-corrected), that is, higher regularity was associated with decreasing RTs. The type of preceding trial (active or passive) did not significantly affect RTs, $F < 1$. However, the interaction *Regularity Level x Preceding*

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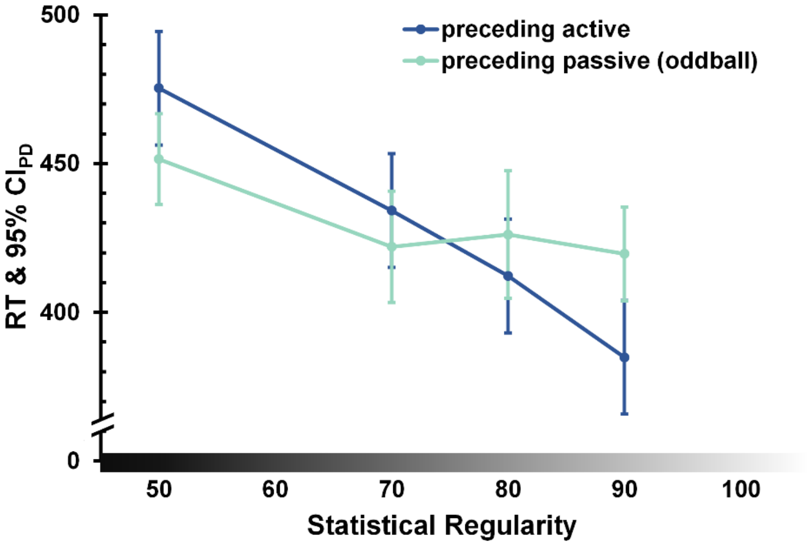
[2] Following a reviewer suggestion we further conducted a control analysis with cumulative link mixed models. Results replicated the ANOVA and LME approaches (control ratings: *Regularity Level*, $z = 21.98$, $p < .001$, *Experiment* (prior vs. present), $z = 22.81$, $p < .001$, *Experiment x Regularity Level*, $z = -12.37$, $p < .001$; predictability ratings: ps < .001).

Trial was significant, $F(3, 255) = 11.61$, $p < .001$, $\eta_p^2 = .12$, $\varepsilon = .82$ (GG-corrected).[3] More specifically, RTs following active trials decreased linearly across regularity levels, whereas RTs following passive trials did not follow this pattern (see Fig. 2). That is, on a descriptive level, RTs were higher after unexpected events (i.e., passive trials) than after regular active trials in the 80% regularity condition, $M_{\text{preceding passive}} = 426$ms (*SD* = 145ms), $M_{\text{preceding active}} = 412$ms (*SD* = 152ms), and the 90% regularity condition, $M_{\text{preceding passive}} = 420$ms (*SD* = 171ms), $M_{\text{preceding active}} = 385$ms (*SD* = 138ms). This differential influence of preceding trial depending on regularity levels implies that post-oddball slowing manifests itself at higher regularities (Notebaert et a., 2009). However, caution should be exercised in interpreting the effects in the 90% regularity condition, as it only included a small number of passive trials per block. Additionally, processing readjustments were evident when comparing performance after correct trials vs. error trials, as indicated by higher average RTs after error trials (i.e., after unexpected incorrect keypresses leading to a blank screen), $M_{\text{preceding incorrect}} = 454$ms (*SD* = 181ms), $M_{\text{preceding correct}} = 402$ms (*SD* = 142ms), $t(74) = 3.09$, $p = .003$, $d_z = 0.36$.[4]

Figure 2

Response times for trials being preceded by active compared to passive trials for different regularity levels



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[3] To assess whether the results of the RT analysis were biased due to unequal cell counts, we fitted linear mixed-effects to the RT data using regularity level and preceding trial as fixed effects and participant as random effect. These analyses replicated the ANOVA results by showing that the interaction of regularity level and preceding trial significantly improved model fit relative to an additive model, $\chi^2(1) = 43.53$, $p < .001$.

[4] The post-error slowing analysis was conducted with a decreased sample size of $n = 75$ participants (compared to all other analyses with the complete $N = 86$), because 11 participants always pressed the correct key in the experimental trials.

Note. Response times (RTs in ms) for different regularity levels for trials that were preceded by active trials and for trials that were preceded by passive (i.e., oddball) trials. Results suggest that post-oddball slowing, i.e., longer RTs following unexpected events, occurs more prominently at higher levels of regularity (in the 80% and 90% regularity condition with 20% or 10% passive trials, respectively). Error bars depict 95% within-subjects confidence intervals of paired differences (CI_{PD}) between RTs following active vs. passive trials computed separately for each regularity level (Pfister & Janczyk, 2013).

2.3. Discussion

Experiment 1 targeted how general statistical regularities in an agent's environment affect SoA. To this end, we manipulated the probability of an event occurring without a prior action p(E|¬A) across 5 levels of statistical regularity (50%, 70%, 80%, 90% or 100% regularity). Higher regularity was associated with higher levels of SoA, implying that the presentation of events in the absence of actions not only affects causal beliefs about action-event associations in the environment (Elsner & Hommel, 2004; Metcalfe et al., 2013), but also impacts action-focused concepts such as SoA. As expected, when manipulating action-related contingency by varying the probability of a non-contingent event following an action as done in our previous study (Schwarz et al., 2022), SoA was affected more than when manipulating general statistical regularity with no direct action link. Prominent agency theories like the internal forward model argue that SoA emerges when the prediction of a consequence by the sensorimotor system following a conducted action matches the actual event (Moore & Fletcher, 2012; Synofzik et al., 2008). The potential to manipulate SoA by inducing such discrepancies between prediction and consequence of own actions was only available in the prior experiment (Schwarz et al., 2022). This type of motor input was not available in the present study, as in passive trials no predictions about sensory consequences generated by own actions could be made as no action was performed.

However, although irregularities in this experiment did not involve action processes, SoA was clearly affected, possibly due to higher-level cognitive processes that may retrospectively adjust SoA by integrating contextual information (Moore & Fletcher, 2012; Synofzik et al., 2008). Such contextual information may include, for instance, important background knowledge about the general probability of critical events, environmental and action-related (Moore et al., 2009). Besides, studies have already shown that a perceived causal connection between an intentional, deliberate non-action and consequence can trigger SoA (Weller et al., 2020), a finding that we could now extend further: Perceived authorship is affected when an event is not exclusively associated with one's own action, but also associated with no action (and no intention to act or not to act) at all.

Interestingly, reductions in SoA seem to be strongest between complete regularity and the adjoining 90% regularity condition in the present setup. Individuals seem to assign great importance to such rare and unexpected events disrupting predictions in a series of frequently occurring events. This phenomenon coincides with research exploring the oddball paradigm: When two events are presented with different probabilities in unpredictable random series, the rarely occurring unusual event at unpredictable times triggers particularly strong electrophysiological responses (Duncan-Johnson & Donchin, 1977; Polich, 2007). These responses are considered to reflect a cognitive process of updating existing models about event probabilities in the environment (Polich, 2007; but see Verleger et al., 2016). Importantly, the probability of rare events occurring affects this oddball effect, with arousal and attention increasing the rarer the unusual event appears (Coulson et al., 1998). Especially rarely occurring novel events, for instance few passive trials in higher regularity levels as the 80% or 90% level, therefore elicited a strong orienting response and subsequent resource-demanding readjusting (Burns et al., 2010). This is also in line with learning processes involved in SoA formation, such as the analysis of prediction errors: When we learn new associations, the first instance of revealing this new association is thought to bring about the strongest learning effect and the biggest change in association strength (Chan et al., 2021; Rescorla & Wagner, 1972).

In this present experiment we could not draw definitive conclusions about SoA formation for singular instances of regularity disruptions, however. To address this limitation, we conducted Experiment 2, in which we explicitly focused on the impact of singular deviating events on SoA. To allow for optimal comparison of both regularity types (action-related and general with no direct action link), we further included both within the same experiment.

3. Experiment 2: Singular deviations from perfect regularity

Experiment 2 replicates the basic setup of Experiment 1 while focusing on near-perfect levels of regularity. This included a 93% (2 irregular trials out of 30) condition and a 97% (1 out of 30) condition, in addition to the previously tested regularity levels of 90% (3 out of 30) and 100% (0 out of 30). As a control condition for better comparison with the previous experiments, we also included the 80% (6 out of 30) regularity level, resulting in a total of 5 conditions (as in Experiment 1). Moreover, we integrated both types of regularity in one experiment: In half of the experiment (Scenario 1 blocks) action-related statistical regularity was varied, i.e., in some cases, the supposedly correct keypress could lead to an unexpected, non-contingent event; however, all events were always preceded by actions. In the other half (Scenario 2 blocks) general statistical regularity was varied, i.e., keypresses always led to a specific, predictable event in 100% of the cases, but in some trials the respective event appeared without a preceding action. Following the results of Experiment 1, we expected SoA to be sensitive to even the smallest changes in statistical regularities, with higher regularity leading to higher SoA judgments. Again, we expected SoA to differ depending on our regularity manipulation and to be more strongly affected by action-related than not action-related, general regularities.

3.1. Method

The preregistration, data, and analyses files are available on the Open Science Framework (https://osf.io/3tz82 and https://osf.io/usdb9).

3.1.1. Participants. We recruited 108 participants via Prolific in the summer of 2022, none of whom took part in Experiment 1. Power calculations were based on an expected effect size of $d_z = 0.3$ to credit the fact that the comparison of 90% vs. 100% regularity of Experiment 1 provides an upper boundary of to-be-expected effects ($d_z = 0.41$). A minimum sample size of 90 participants provided sufficient power of $1-\beta = .8$ and $\alpha = .05$ (pwr package, RStudio, 2020), to which we added an extra 20% to account for possible drop-outs. Five participants were excluded based on the post-experimental questionnaire, because they admitted to not having concentrated properly on the task (*n* = 2), not having answered the ratings truthfully (*n* = 2) or not having tried to generate as many smiling faces as possible (*n* = 1). These criteria were already predetermined in the preregistration. Furthermore, a considerable number of participants (*n* = 13) was excluded, as they pressed a key in more than 12 (33.3%) passive trials throughout the experiment, although they were explicitly instructed not to do so. Detailed results concerning the post-experimental questionnaire can be found in Table S5 in the Supplementary Material. The final sample size for statistical analysis comprised 90 participants and retained a power of $1-\beta = .80$. Mean age of the adjusted sample was 39.2 years (*SD* =

13.4, range 19-66) with 41 participants identifying as male, 48 as female and 1 as non-binary. Seventy-seven individuals reported being right-handed, 12 left-handed, and 1 ambidextrous. Fourteen different nationalities were reported, with the most common countries being the UK (*n* = 40), South Africa (*n* = 15) and the USA (*n* = 9). Participants gave informed consent prior to the experiment and received monetary compensation for participation.

3.1.2. Apparatus, design and procedure. Stimuli and procedure of Experiment 1 were slightly adapted and changed because of the scenario (manipulations in action-related statistical regularity and general statistical regularity within the same experiment) and modified regularity levels. Now, 5 of 10 blocks varied in the ratio of contingent to non-contingent trials (Scenario 1), and the other 5 blocks varied in the ratio of active to passive trials (Scenario 2). Regularity manipulations included levels of 80%, 90%, 93%, 97% and 100%. For instance, the 93% condition included 2 irregular trials (either non-contingent or passive trials, depending on scenario) per 30-trial-rating-section. Again, the task was to produce as many smiling faces as possible during the experimental blocks by pressing either the A or L key with their left or right index finger, respectively (as before, the effective key was randomized across blocks but stayed the same within one block), and to rate perceived control and predictability when indicated. Depending on the scenario, participants received two different instructions: In Scenario 1 (manipulation of action-related statistical regularity), participants were asked to press a key in all trials but were informed that sometimes their keypress might result in an unexpected event. In Scenario 2 (manipulation of general statistical regularity), participants were instructed that, although they should press a key in most trials, sometimes they might be asked not to press any key at all (see Fig. 3A). In general, they were advised to concentrate and pay attention, respond as quickly as possible and only press a key when they were explicitly asked to do so.

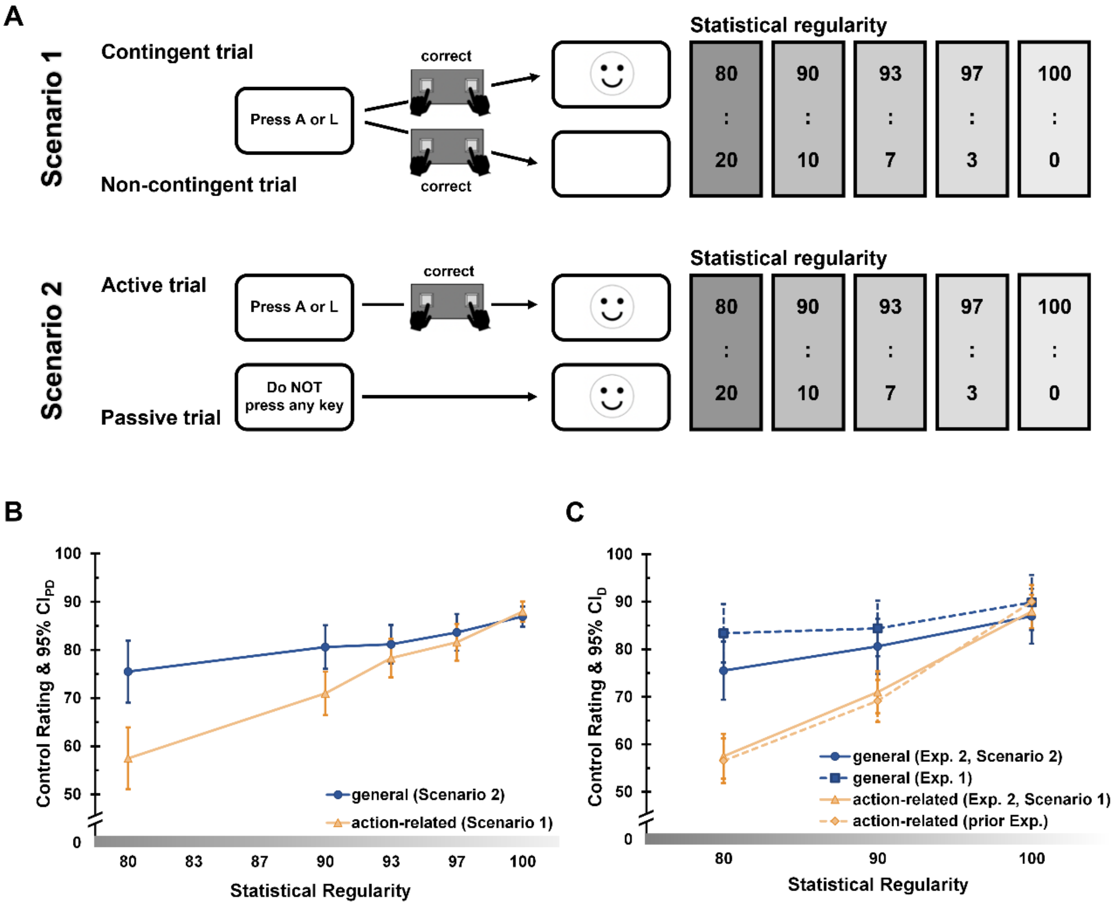
A detailed overview of the experimental procedure of Experiment 2 can be found in the Supplementary Material (Fig. S1). Scenario 1 trials always started with the cue “Press A or L” presented until the participant pressed one of the two keys. In contingent trials, the correct keypress led to a smiling face while the incorrect keypress led to a blank screen (in non-contingent trials this mapping was exactly reversed). Each possible consequence after a keypress was displayed for 600 ms, followed by an 800 ms intertrial interval. Scenario 2 trials could start with the prompt “Press A or L” in active trials, after which the participant pressed a key resulting in either a smiling face after a correct keypress or a blank screen after an incorrect keypress (displayed for 600 ms), or with the prompt “Do NOT press any key” in passive trials. This prompt was displayed for 700 ms (simulating a standard reaction time in active trials) and then automatically followed by the smiling face presented for 600 ms and again an 800 ms intertrial interval. In the particular case that a participant pressed a key in a passive trial, a warning ("You pressed a key. Trial will start again.") was displayed for 2000 ms, after which the trial was aborted and restarted. Because passive trials were so rare in this experiment, we expected participants to show a strong tendency towards pressing a key in all trials (Wessel, 2018). However, such a keypress would automatically transform a passive trial into an active one as the subsequent appearance of a smiling emoticon would evoke a pseudo-effectual experience (the keypress would not have a causal effect, but it would be perceived as having a causal effect). As most regularity levels only employed very few passive trials, such a transformation would render the whole data set uninterpretable. To avoid this outcome, we thus chose to abort the ongoing trial and include an error message and a trial repeat when a key was pressed during passive trials. This ensured that all passive trials of any block actually remained passive trials, and, likewise, that the number of completed active trials still remained as intended as the aborted trials were markedly different from either passive or active trials and would likely not be perceived as either. Please note, however, that we still excluded participants who showed a high number of such error trials (more than 12 keypresses during passive trials) to avoid any confound due to too many errors (see *Participants* subsection 3.1.1.).

Taken together, the 2 (type of regularity) x 5 (regularity level) design of Experiment 2 resulted in 10 different blocks presented in randomized order. Compared to the first experiment, the number of experimental trials and ratings per block was increased, as every possible block composition only existed once: Now each block consisted of 5 practice trials, 90 test trials and 3 control and predictability ratings (after 30, 60, and 90 trials).

After completing the experimental blocks, participants were asked about their performance regarding effort, focus, and attention, as well as language and comprehension problems. It was clearly indicated that negative responses to any of these questions would not have consequences of any kind for the participants.

Figure 3

Study design and main results of Experiment 2



Note. (A) Study design of Experiment 2 showing the 5 different regularity levels. For action-related statistical regularity (Scenario 1 blocks), the ratio of contingent trials to non-contingent trials (i.e., p(E|A)) was varied. For general statistical regularity (Scenario 2 blocks), the ratio of active trials to passive trials (i.e., p(E|¬A)) was varied. Higher regularity included fewer irregular trials compared to regular trials. In both contingent trials and active trials the correct keypress led to a presentation of the smiling face. On the other hand, in non-contingent trials a blank screen appeared after a correct keypress and in passive trials the smiling face appeared without any prior action. (B) Perceived control was rated higher when regularity increased. This effect was evident for both regularity manipulations (action-related statistical regularity and general statistical regularity). Futhermore, participants were especially sensitive for singular instances of regularity disruption (97% vs. 100%) in both scenarios. Significant differences in perceived control between Scenario 1 and Scenario 2 were found in the 80% condition and the 90% condition. Error bars depict 95% within-subjects confidence intervals of paired differences (CI_{PD}) between Scenario 1 vs. Scenario 2 computed separately for each regularity level (Pfister & Janczyk, 2013). (C) Comparison of mean control ratings in all 4 experimental scenarios (with our prior study, Schwarz et al. (2022), and Experiment 1 depicted in dashed lines, and both scenarios of Experiment 2 depicted in solid lines). Control was rated very similarly in experimental tasks with manipulations in action-related regularity (lighter orange lines), whereas for general statistical regularity (darker blue lines) slightly less control was experienced in Experiment 2 compared to Experiment 1, especially for 80% regularity levels. Error bars depict 95% between-subjects confidence intervals of mean differences (CI_D), computed separately for comparisons between experimental tasks for each regularity level (Pfister & Janczyk, 2013).

3.1.3. Data Analysis. We conducted rmANOVAs with the within-subjects factor *Regularity Level* (80% vs. 90% vs. 93% vs. 97% vs. 100%), and the within-subjects factor *Type of Regularity* (action-related statistical regularity vs. general statistical regularity) separately for each dependent variable (control and predictability rating). We employed two-tailed paired *t*-tests as follow-up tests for pairwise comparisons with corresponding effect sizes calculated as $d_z = \frac{t}{\sqrt{n}}$. To evaluate the relationship between predictability and control ratings we implemented the within-subjects factor *Rating* (control vs. predictability) in the aforementioned rmANOVA.

By fitting two mixed-effects models, again with statistical regularity as the fixed effect, along with random slopes and random intercepts (Oberauer, 2022), marginal and conditional R^2 could be computed to evaluate and contrast explained variances by the complete model as well as by the fixed factor, i.e., action-related statistical regularity or general statistical regularity with no direct action link (lmer package, RStudio, 2020).

As a secondary analysis, we compared perceived control in the 80%, 90% and 100% condition with the corresponding ratings of the two previous experiments. One mixed-design ANOVA was conducted to analyze differences in ratings between experiments in which action-related statistical regularity was varied (our prior experiment, Schwarz et al., 2022, vs. Scenario 1 of the present experiment) and a second analogous ANOVA focused on differences in ratings between experiments in which general statistical regularity was varied (Experiment 1 vs. Scenario 2 of the present experiment). Accordingly, these ANOVAs included the between-subjects factor *Experiment* and the within-subjects factor *Regularity Level* (80% vs. 90% vs. 100%) and were followed up by *t*-tests for independent samples.

We did not analyze performance data because oddball events were particularly rare in this experiment, thus not providing sufficiently many trials for meaningful analysis.

3.2. Results

Fig. 3B shows mean control ratings in Scenario 1 vs. Scenario 2 depending on type of regularity and regularity level. Fig. 3C shows a comparison of mean control ratings for type of regularity and regularity level in both present experiments as well as in our prior study (Schwarz et al., 2022).

3.2.1. Impact of regularity depending on level and type. Control ratings were sensitive even to small changes in regularities, action-related or otherwise, main effect *Regularity Level*, *F*(4, 356) = 59.03, $p < .001$, $\eta_p^2 = .40$, $\varepsilon = .64$ (GG-corrected). For both types of regularity, higher probabilities of regular trials resulted in higher control ratings (see Table 2). Significant differences emerged especially for the inclusion of a single deviating trial, i.e. comparing the 97% with the 100% condition for either regularity type, $M_{\text{action-related, Diff}} = 6.36$, $t(89) = 3.81$, $p < .001$, $d_z = 0.40$, $M_{\text{general, Diff}} = 3.30$, $t(89) = 2.32$, $p = .023$, $d_z = 0.24$. Further singular incidences of regularity disruption did not lead to significant SoA decreases when general statistical regularity was manipulated, with the impact of irregularity decreasing with each further instance. However, when action-related statistical regularity was manipulated, the difference from 2 to 3 irregular trials (90% vs. 93%) also indicated a significant difference, $M_{\text{action-related, Diff}} = 7.33$, $t(89) = 4.85$, $p < .001$, $d_z = 0.51$, suggesting that rare experiences of irregularity might have a different impact on the experience of agency depending on action-related or general statistical regularity. When applying Bonferroni-correction to account for multiple comparisons, significances for pairwise comparisons for action-related regularity did not differ. However, the difference between the 97% and 100% condition for general statistical regularity was no longer statistically significant and results should therefore be interpreted with caution (see Table S3).

In general, action-related statistical regularity affected SoA more strongly than general statistical regularity with no direct action link, overall $M_{\text{Scenario1}} = 75.27$, overall $M_{\text{Scenario2}} = 81.58$, main effect *Type of Regularity*, $F(1, 89) = 20.54$, $p < .001$, $\eta_p^2 = .19$. This effect was especially evident in lower regularity levels, interaction *Regularity Level x Type of Regularity*, $F(4, 356) = 15.64$, $p < .001$, $\eta_p^2 = .15$, $\varepsilon = .70$ (GG-corrected), also confirmed by significant differences in separate two-tailed paired *t*-tests between both scenarios in the 80%, $t(89) = 5.57$, $p < .001$, $d_z = 0.59$, and the 90% regularity level, $t(89) = 4.23$, $p < .001$, $d_z = 0.45$, whereas differences remained not significant for the other three regularity levels, all *p*s > .159.

The results for predictability ratings mirror these findings (see details for the ANOVA and pairwise comparisons with and without Bonferroni-correction in Table S4 in the Supplementary Material). Control and predictability ratings did not differ significantly, $F < 1$.

When comparing linear fits of mixed-effects models, the complete action-related statistical regularity model explained 79.02% of the measured variance (conditional R^2), with the fixed factor (action-related statistical regularity) accounting for 17.83% of that variance (marginal R^2). On the other hand, for general statistical regularity the complete model explained 81.31% of the measured variance (conditional R^2), with the fixed factor (general statistical regularity) explaining 2.63% of that variance (marginal R^2). In line with expectations, these regressions show that action-related statistical regularity had a stronger impact on differences in SoA than general statistical regularity. Nevertheless, adding the fixed factor significantly improved model quality in both models, action-related statistical regularity: $\chi^2(1) = 63.75$, $p < .001$, general statistical regularity: $\chi^2(1) = 23.94$, $p < .001$.[5]

Table 2

Pairwise comparisons of mean control ratings for different regularity levels, for both action-related statistical regularity ($M_{Scenario1}$) and general statistical regularity with no direct action link ($M_{Scenario2}$)

Regularity	$M_{Scenario1}$	Pairwise comparisons		$M_{Scenario2}$	Pairwise comparisons	
80%	57.48			75.51		
90%	70.98	*80% vs. 90%*	$t(89) = 6.17$, $p < .001$, $d_z = 0.65$	80.60	*80% vs. 90%*	$t(89) = 3.02$, $p = .003$, $d_z = 0.32$
93%	78.31	*90% vs. 93%*	$t(89) = 4.85$, $p < .001$, $d_z = 0.51$	81.17	*90% vs. 93%*	$t(89) = 0.38$, $p = .707$, $d_z = 0.04$
97%	81.60	*93% vs. 97%*	$t(89) = 1.72$, $p = .089$, $d_z = 0.18$	83.65	*93% vs. 97%*	$t(89) = 1.53$, $p = .130$, $d_z = 0.16$
100%	87.96	*97% vs. 100%*	$t(89) = 3.81$, $p < .001$, $d_z = 0.40$	86.95	*97% vs. 100%*	$t(89) = 2.32$, $p = .023$, $d_z = 0.24$

3.2.2. Comparison of control ratings of Exp. 2 vs. Exp. 1 and our previous study (Schwarz et al., 2022). First, we compared the impact of action-related statistical regularity on SoA between experiments (previous study vs. Exp. 2 Scenario 1), and incorporated all levels of regularity included in both our prior experiment (Schwarz et al., 2022) and Experiment 2, i.e., the 80%, 90%, and 100% regularity level. Action-related statistical regularity again affected SoA, $F(2, 1158) = 478.16$, $p < .001$, $\eta_p^2 = .45$, $\varepsilon = .91$ (GG-corrected), but the data did not show an impact of *Experiment*, $F < 1$, nor of the interaction *Experiment x Regularity Level*, $F(2, 1158) = 1.93$, $p = .150$, $\eta_p^2 < .01$, $\varepsilon = .91$ (GG-corrected), indicating that participants experienced control at a very similar level in all three examined regularity levels between experiments. A slightly different picture emerged when analyzing data from experimental tasks that involved manipulations of general statistical regularity (Exp. 1 vs. Exp. 2 Scenario 2). Level of regularity also affected SoA in this analysis, $F(2, 348) = 32.79$, $p < .001$, $\eta_p^2 = .16$, $\varepsilon = .93$ (GG-corrected). Additionally, the data also revealed slight differences in control ratings between experiments on a descriptive level. Mean control ratings were marginally lower in Experiment 2, particularly in the 80% condition, $M_{80\%,\ Exp2} = 75.51$, $M_{80\%,\ Exp1} = 83.35$ (see Fig. 3C). However, these differences did not reach significance in corresponding tests, main effect *Experiment*, $F(1, 174)$

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[5] Following a reviewer suggestion we further conducted a control analysis with cumulative link mixed models. Results replicated the ANOVA and LME approaches (control ratings: *Regularity Level*, $z = 15.60$, $p < .001$, *Type of Regularity* (action-related vs. general), $z = 7.16$, $p < .001$, *Regularity Level x Type of Regularity,* $z = -2.60$, $p = .009$; predictability ratings: *p*s < .002).

= 3.27, p = .072, η_p^2 = .02, interaction *Experiment x Regularity Level*, $F(2, 348)$ = 2.73, p = .071, η_p^2 = .02, ε = .93 (GG-corrected).

3.3. Discussion

In Experiment 2, we manipulated both action-related contingency and general statistical regularity for high-regularity levels to study the impact of singular instances of regularity disruption on SoA. SoA was sensitive to small deviations from perfect contingency for both types of regularity, i.e., for specific action-related statistical regularity as well as general statistical regularity with no direct action link. Consistent with our expectations, SoA increased continuously with higher regularity, indicating that violations of learnt causal beliefs about action-event associations, e.g., by presenting unexpected events after conducting an action or by manipulating the probability of events appearing in general without prior actions, lead to a diminished perception of control over the environment by performing certain actions (Behrens et al., 2007; Buehner, 2005; Moore, 2016).

In line with results of Experiment 1 and our prior study (Schwarz et al., 2022), violations of action-related contingency again led to stronger impairments in SoA than violations in general statistical regularity. Now, we observed the influence of different types of regularity within one experiment, allowing for a cleaner comparison and eliminating possible differences due to sample characteristics. In the current experiment, general statistical regularity with no direct action link could explain about 3% of the variation in perceived control, whereas directly action-related regularity accounted for about 18% of the measured variance in control ratings. This indicates that SoA is indeed especially sensitive to regularity disruptions that pertain directly to own actions. Importantly, however, the impact of general statistical regularity on SoA formation shows that SoA goes beyond own actions and takes general environmental regularities into account.

Moreover, our data stress that even singular irregular trials appearing in a series of 30 regular trials significantly reduced perceived control. In contrast, despite equal linear increments of one irregular trial per condition, SoA scores did not change significantly when the number of irregular trials was increased from one to two (97% and 93% condition) or from two to three (93% and 90% condition) per 30-trial-section for instances of general statistical regularity. However, incontingent action-effect trials showed a slightly different pattern with the increase from 2 to 3 irregular trials also being weighed disproportionally strongly. The current results suggest a great importance of complete vs. almost complete regularity. The impact of the minimal possible number of one irregular trial per 30-trial-section, i.e., the impact of one oddball (Duncan-Johnson & Donchin, 1977), might have caused overly strong activation and subsequently inflated attention and processing of such an occurrence (Burns et al., 2010; Coulson et al., 1998).

When integrating control rating results of Experiment 2 in a comparison of all conducted experimental tasks, we demonstrated once more that displaying unexpected events after a voluntary action impacts SoA differently than displaying events without any prior action. Some slight discrepancies to Experiment 1 results could be observed, as control ratings were marginally lower in general statistical regularity conditions of Experiment 2. Possible post-hoc explanations include, for instance, that due to the very high regularity in Experiment 2, participants might have become very accustomed to the fact that they were in control. This may have made participants very sensitive to any instance of irregularity resulting in large reductions of perceived control. Another potential aspect that might have further reduced the mean control scores in Experiment 2 is the novel implementation of trial repetitions, as passive trials were modified so that in cases of redundant keypresses the trial could be aborted and repeated. In such situations a salient warning was displayed that might have captured attention resulting in a demanding readjustment to the task, a disruption in the workflow and further loss of control (Theeuwes, 2010). However, the difference between the result patterns of Experiment 2 and Experiment 1 was numerically very small, signifying that across all experimental tasks, findings were very robust and reliable.

When considering all the participants involved, no constraints on the generality of the results were identified. The experiments included diverse groups of individuals with a wide range of nationalities and ages, and the methods allowed for flexibility, as participants contributed from their home computers, without strict laboratory requirements. In this context, it is important to acknowledge that viewing distance varied among participants. Nevertheless, since all participants worked on a computer or laptop and interacted with a keyboard, we are confident that the viewing distance was comparable.

4. General Discussion

4.1. Theoretical Implications

The present experiments targeted SoA in environments with varying statistical regularities, action-related or otherwise, and thus provoking mismatches between expectations and actual events. Experiment 1 aimed for an extension of our previous findings (Schwarz et al., 2022) and asked whether wide range variations in $p(E|\neg A)$, i.e., the probability of an event occurring without prior action, would affect explicit SoA judgments. While SoA research commonly involves contingency manipulations where an unexpected event follows an action (Metcalfe et al., 2013; Penton et al., 2018), we focused on contingency violations characterized by anticipated events that occur without the preceding triggering action. SoA evaluations, by definition, pertain to the perceived control and authorship over one's own actions and their consequences in the environment, encompassing both low-level sensorimotor processes and high-level postdictive judgment processes. Our studies revealed that SoA extends beyond the traditional concept tied to one's own actions and additionally incorporates general statistical regularities in the environment, even when not directly linked to specific actions. These findings suggest a conceptualization of SoA that not only includes the conventional concept involving own actions, but that also accounts for general statistical regularities of the environment. Thus, as the disturbances of regularity we implemented in our studies were not directly linked to one’s own actions, our setup allowed for investigating SoA as a concept that might go beyond own actions towards a more generalized representation of control regarding environmental events.. Experiment 2, then, contrasted the separate influences of the two parts of the contingency formula – $p(E|A)$ and $p(E|\neg A)$ – on SoA in modified conditions in which only singular irregular situations disrupted perfect regularity.

Our data provide evidence that SoA summary ratings indeed were more sensitive to irregularities involving one’s own actions than to irregularities occurring without a direct involvement of own actions. This finding is in accordance with the conceptualization of SoA itself as perceived control over our actions and our environment through those actions. Thus, the ability to conduct actions freely and voluntarily is seen as a crucial contributor to SoA formation and to perceiving control over actions and following events (e.g., Barlas et al., 2017; Moore, 2016; Sidarus et al., 2017; Wegner & Wheatley, 1999). When such a deliberately performed action leads to a non-contingent, unexpected event, predictions and beliefs about one’s own efficacy are violated (Jeannerod, 2009).

Nevertheless, general statistical regularity had a systematic and significant influence on SoA, albeit smaller in size than action-related regularity. When holding $p(E|A)$ constant, summary SoA ratings were significantly affected by appearances of the event in question without prior actions. This finding provides evidence that SoA formation incorporates more regularity information than occurrences directly related to and produced by one’s own actions. That is, while SoA remains most strongly affected by action-related consequences, it is also sensitive – although to a lesser degree – to environmental occurrences that are not directly linked to one’s own actions. Please note, however, that in the conducted experiments, these environmental occurrences were indirectly associated with the action, as the environmental event in question was equivalent to the action consequence in active trials. An interesting question for future research could be if also completely unrelated occurrences in the environment would still impact the subjective control experience for another event.

Our findings are corroborated by previous considerations suggesting that SoA can be influenced by contextual information (Moore & Fletcher, 2012; Synofzik et al., 2008), like background knowledge on probabilities of critical events occurring or not, may that be in the presence or absence of an action (Elsner & Hommel, 2004; Metcalfe et al., 2013; Moore et al., 2009). The occurrence of an event without prior action might affect our perception of the event as not-controllable, or at least not-controllable by us. This in turn might retrospectively lead us to question our control of previous instances of event production, even if we had complete control over those events. Thus, such instances of regularity disturbance may call into question our understanding of predictability, intentionality and authorship (Wegner, 2004).

The impact of irregularities in the environment on SoA, action-related or otherwise, was evident even when presenting only very few instances of irregular events. In accordance with our results, unusual events that were subjectively perceived as rare, salient and task-relevant seem to be processed differently than other events (Coulson et al., 1998). In line with this general notion, our data extend previous findings on regularity and SoA (e.g., Majchrowicz & Wierzchoń, 2018; Schwarz et al., 2022) by highlighting a striking impact of singular disturbances of perfect statistical regularity. Moreover, our data indicate that such effects can also emerge for situations in which the oddball occurs in the absence of an action.

Besides the processing of oddballs, another possible explanation for the remarkable reduction in SoA between complete regularity and almost complete regularity is that sensitivity seems to be greatest for probability changes near 0% or 100% relative from a reference point (Burns et al., 2010; Tversky & Kahneman, 1992). This concept of diminishing sensitivity is captured by the assumption that individuals do not weigh events by their actual probabilities, but by distortions of them (Tversky & Kahneman, 1992). For instance, most people would regard a change from 99% regularity to 100% regularity as significant, as it shifts predictability of what could happen in the environment from almost perfect to completely perfect. In contrast, a change in regularity from 83% to 84% would be seen as inconsequential, because, although it likewise objectively increases regularity by 1%, the fundamental expectation of perfect regularity in the environment is violated in either case. In other words, increasing the number of irregular trials from zero to one disrupts perfect predictability of which trial will be presented next and is therefore of especially high relevance for the participants' perceived control. In a real-world context, one could think of this as analogous to the proportion of times a cell phone call successfully goes through. In that instance, a single failed call can be particularly salient, as it may signify an issue with the phone. The same change in proportion of occurrences when the phone drops a call on three instead of four out of every ten instances would not be as informative, as the phone appears to be malfunctioning in both cases.

There are other reasons for why changes in regularity may not be perceived linearly. For example, theories of stimulus discrimination state that the discriminability of two numbers decreases as the magnitude of numbers increase (Moyer & Landauer, 1967). Following Weber’s and Fechner’s law (1860), with a higher number of stimuli, i.e., a higher number of irregular trials, the detection of any change in number becomes more difficult as discriminability decreases with the strength of the pre-existent stimulus (the higher pre-existent percentage of irregular trials). Thus, assumptions of psychophysics state that the difference between no irregularity at all and a few irregular trials is more salient than the further additions of irregular trials, as stimulus detection weakens when adding more and more stimuli. Whether or not these considerations hold for contingency manipulations in other experimental setups or more complicated situations involving more than one agent may provide a fruitful avenue for future studies.

Finally, the impact of one singular, irregular trial on SoA formation, potentially bolstered by the mechanisms discussed above, mirrors the idea of the strength of prediction errors involved in learning processes (Chan et al., 2021; Rescorla & Wagner, 1972). Learning novel associations pertaining either to one’s own actions or simply to the environment is crucial for an individual’s ability to adapt to dynamic environments. The sensitivity of SoA to singular disruption events may reflect a byproduct of an organism’s orientation towards such learning opportunities. Or, possibly, it could signify that SoA may be directly associated with learning processes, especially those pertaining to oneself.

4.2. Limitations

Conceptually, explicit ratings of SoA do not provide an objective but rather a subjective representation of the actor as the cause of environmental changes. This subjectivity makes SoA attributions vulnerable to cognitive biases, such as self-efficacy beliefs (Bandura, 1982). The controversy extends to the rating process itself, where biases, like social desirability effects (Krumpal, 2013), may influence self-report responses independently of the SoA or general self-concepts.

However, implicit SoA measures such as temporal binding or sensory attenuation are also discussed controversially in the community (Schwarz et al., 2019; Antusch et al., 2021). For instance, the reliability of temporal binding has been questioned, revealing discrepancies among measurement methods (Siebertz & Jansen, 2022) and methodological confounds (Gutzeit et al., 2023; Schwarz & Weller, 2023). Further, the conceptual association of temporal binding with SoA has been challenged, suggesting alternative explanations such as causality, partial multisensory integration, and attentional processes (Klaffehn et al., 2021; Schwarz & Weller, 2023). Sensory attenuation as another implicit SoA measure is often considered a universal principle across all sensory modalities, but predominantly studied in tactile and auditory modalities (e.g., Bays et al., 2006; Blakemore et al., 1999; Fuehrer et al., 2022; Harrison et al., 2021; Horváth, 2015). Critically, studies on sensory attenuation in the visual domain are sparse and their findings ambiguous (Cardoso-Leite et al., 2010; Desantis et al., 2014; Hughes & Waszak, 2011; Mifsud et al., 2016; Yon & Press, 2017).

Given the current discussion, we chose explicit SoA ratings in our experiments. Clarity in study design and interpretation was, of course, essential to account for possible biases. Additionally, many of our analyses focused on within-subject comparisons, potentially reducing biases based on individual leanings with regard to self-efficacy etc. Moreover, our own previous work suggests that, indeed, there is only little association between individual parameters such as self-efficacy and perceived control ratings in most instances (Schwarz et al., 2022). Thus, we are confident that the utilized ratings are adequate in measuring the participants experienced control throughout the experiments.

4.3. Future research

Although we investigated how top-down beliefs about regularities in the environment affect SoA, we did not take other contextual factors into account that have already been demonstrated to be important for SoA formation. These include the timing of events (e.g., van der Wel & Knoblich, 2013) or the social context of either working alone or working together with a partner (Loehr, 2022; Moore & Obhi, 2012; Schwarz et al., 2023) while learning a task (e.g., van der Wel et al., 2012). Repeating the current experiment in such a social context could affect the participants’ SoA formation considerably, especially for general statistical regularity that does not pertain to one’s own actions: While the appearance of the smiling face in passive trials is most likely assigned to the inanimate environment such as the computer, within a social context, participants might attribute the event to their co-agent. As joint actions are known to generate not only self-related SoA, but also the so-called “we-agency” (Pacherie, 2014; Schwarz et al., 2023; van der Wel, 2015), i.e., an agentive identity pertaining to more than one agent, perceived control might remain high even in those circumstances, depending on various aspects of the social experience (competition vs. cooperation, etc.).

5. Conclusion

Taken together, our results indicate that the agentic experience generally draws on causal beliefs about regularities in the environment, action-related and otherwise, allowing an interpretation of SoA as a subjective counterpart to this sensitivity to environmental regularity. However, they also show that, during SoA formation, different types of regularity are given differential weight depending on their relation to own actions, and singular instances of regularity disturbance are being disproportionally incorporated, characterizing SoA not as an objective regularity detector, but rather a highly subjective interpretation of perceived regularities based on relevance. This adaptability of SoA may allow individuals to insert themselves clearly into their surrounding environment. Doing so may help in putting emphasis on their role as an agent rather than observer and may support being oriented towards surprising events that signify learning opportunities.

In this series of experiments, we report how summary scores of sense of agency dynamically adapt to situational changes in regularity, action-related and otherwise. We show that perceived control is sensitive to statistical regularity concerning especially, but not exclusively, action-related events, providing further support for the importance of environmental regularity for SoA, and providing evidence that SoA formation goes beyond own actions towards a more generalized, subjective representation of control regarding environmental events. We show that a special prominence lies with singular events disrupting perfect environmental regularity.

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CRediT authorship contribution statement

OS and KAS had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: OS, KAS, RVDW, RP. Acquisition of data: OS, MR. Analysis and interpretation of the data: OS, KAS. Drafting of the manuscript: OS. Editing of the manuscript: KAS, RP, RVDW, MR. General Resources: KAS. Obtained funding: KAS. Study supervision: KAS.

References

Antusch, S., Custers, R., Marien, H., & Aarts, H. (2021). Intentional action and limitation of personal autonomy. Do restrictions of action selection decrease the sense of agency? *Consciousness and Cognition*, *88*, 103076. https://doi.org/10.1016/j.concog.2021.103076

Bandura, A. (1982). Self-efficacy mechanism in human agency. *American Psychologist*, *37*(2), 122–147. https://doi.org/10.1037/0003-066X.37.2.122

Barcelo, F., Escera, C., Corral, M. J., & Periáñez, J. A. (2006). Task switching and novelty processing activate a common neural network for cognitive control. *Journal of Cognitive Neuroscience*, *18*(10), 1734–1748. https://doi.org/10.1162/jocn.2006.18.10.1734

Barlas, Z., Hockley, W. E., & Obhi, S. S. (2017). The effects of freedom of choice in action selection on perceived mental effort and the sense of agency. *Acta Psychologica*, *180*, 122–129. APA PsycInfo®. https://doi.org/10.1016/j.actpsy.2017.09.004

Bays, P. M., Flanagan, J. R., & Wolpert, D. M. (2006). Attenuation of Self-Generated Tactile Sensations Is Predictive, not Postdictive. *PLoS Biology*, *4*(2), e28. https://doi.org/10.1371/journal.pbio.0040028

Behrens, T. E. J., Woolrich, M. W., Walton, M. E., & Rushworth, M. F. S. (2007). Learning the value of information in an uncertain world. *Nature Neuroscience*, *10*(9), 1214–1221. https://doi.org/10.1038/nn1954

Berti, S., & Schröger, E. (2001). A comparison of auditory and visual distraction effects: Behavioral and event-related indices. *Cognitive Brain Research*, *10*(3), 265–273. https://doi.org/10.1016/S0926-6410(00)00044-6

Blakemore, S.-J., Frith, C. D., & Wolpert, D. M. (1999). Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience*, *11*(5), 551–559. https://doi.org/10.1162/089892999563607

Buehner, M. J. (2005). Contiguity and covariation in human causal inference. *Learning & Behavior*, *33*(2), 230–238. https://doi.org/10.3758/bf03196065

Burns, Z., Chiu, A., & Wu, G. (2010). Overweighting of small probabilities. *Wiley Encyclopedia of Operations Research and Management Science*, 1–8.

Cardoso-Leite, P., Mamassian, P., Schütz-Bosbach, S., & Waszak, F. (2010). A new look at sensory attenuation: Action-effect anticipation affects sensitivity, not response bias. *Psychological Science*, *21*(12), 1740–1745. https://doi.org/10.1177/0956797610389187

Castegnetti, G., Tzovara, A., Khemka, S., Melinščak, F., Barnes, G. R., Dolan, R. J., & Bach, D. R. (2020). Representation of probabilistic outcomes during risky decision-making. *Nature Communications*, *11*(1), 2419. https://doi.org/10.1038/s41467-020-16202-y

Chan, Y. Y., Westbrook, R. F., & Holmes, N. M. (2021). Protecting the Rescorla–Wagner (1972) theory: A reply to Spicer et al. (2020). *Journal of Experimental Psychology: Animal Learning and Cognition*, *47*(2), 211–215. https://doi.org/10.1037/xan0000271

Coulson, S., King, J. W., & Kutas, M. (1998). Expect the unexpected: Event-related brain response to morphosyntactic violations. *Language and Cognitive Processes*, *13*(1), 21–58. https://doi.org/10.1080/016909698386582

Desantis, A., Mamassian, P., Lisi, M., & Waszak, F. (2014). The prediction of visual stimuli influences auditory loudness discrimination. *Experimental Brain Research*, *232*(10), 3317–3324. https://doi.org/10.1007/s00221-014-4001-2

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. *Psychophysiology*, *14*(5), 456–467. https://doi.org/10.1111/j.1469-8986.1977.tb01312.x

Eitam, B., Kennedy, P. M., & Tory Higgins, E. (2013). Motivation from control. *Experimental Brain Research*, *229*(3), 475–484. https://doi.org/10.1007/s00221-012-3370-7

Elsner, B., & Hommel, B. (2004). Contiguity and contingency in action-effect learning. *Psychological Research*, *68*(2), 138–154. https://doi.org/10.1007/s00426-003-0151-8

Fechner, G. T. (1860). *Elemente der Psychophysik* (UBHD-1152871). Breitkopf & Härtel.

Fuehrer, E., Voudouris, D., Lezkan, A., Drewing, K., & Fiehler, K. (2022). Tactile suppression stems from specific sensorimotor predictions. *Proceedings of the National Academy of Sciences*, *119*(20), e2118445119. https://doi.org/10.1073/pnas.2118445119

Gutzeit, J., Weller, L., Kürten, J., & Huestegge, L. (2023). Intentional binding: Merely a procedural confound? *Journal of Experimental Psychology: Human Perception and Performance*, *49*(6), 759–773. https://doi.org/10.1037/xhp0001110

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience*, *5*(4), 382–385. https://doi.org/10.1038/nn827

Haggard, P., & Tsakiris, M. (2009). The experience of agency: Feelings, judgments, and responsibility. *Current Directions in Psychological Science : A Journal of the American Psychological Society*, *18*, 242–246. https://doi.org/10.1111/j.1467-8721.2009.01644.x

Harrison, A. W., Mannion, D. J., Jack, B. N., Griffiths, O., Hughes, G., & Whitford, T. J. (2021). Sensory attenuation is modulated by the contrasting effects of predictability and control. *NeuroImage*, *237*, 118103. https://doi.org/10.1016/j.neuroimage.2021.118103

Henninger, F., Shevchenko, Y., Mertens, U. K., Kieslich, P. J., & Hilbig, B. E. (2022). Lab. Js: A free, open, online study builder. *Behavior Research Methods*, *54*(2), 556–573.

Holland, P. C., & Schiffino, F. L. (2016). Mini-review: Prediction errors, attention and associative learning. *Neurobiology of Learning and Memory*, *131*, 207–215. https://doi.org/10.1016/j.nlm.2016.02.014

Hon, N., Seow, Y.-Y., & Pereira, D. (2018). Outside influence: The sense of agency takes into account what is in our surroundings. *Acta Psychologica*, *186*, 104–109. https://doi.org/10.1016/j.actpsy.2018.03.004

Horváth, J. (2015). Action-related auditory ERP attenuation: Paradigms and hypotheses. *Brain Research*, *1626*, 54–65. https://doi.org/10.1016/j.brainres.2015.03.038

Hubbard, T. L. (2013). Phenomenal Causality I: Varieties and Variables. *Axiomathes*, *23*(1), 1–42. https://doi.org/10.1007/s10516-012-9198-8

Hughes, G., & Waszak, F. (2011). ERP correlates of action effect prediction and visual sensory attenuation in voluntary action. *NeuroImage*, *56*(3), 1632–1640. https://doi.org/10.1016/j.neuroimage.2011.02.057

Jeannerod, M. (2009). The sense of agency and its disturbances in schizophrenia: A reappraisal. *Experimental Brain Research*, *192*(3), 527–532. https://doi.org/10.1007/s00221-008-1533-3

Karsh, N., Eitam, B., Mark, I., & Higgins, E. T. (2016). Bootstrapping agency: How control-relevant information affects motivation. *Journal of Experimental Psychology: General*, *145*(10), 1333–1350. https://doi.org/10.1037/xge0000212

Klaffehn, A. L., Sellmann, F. B., Kirsch, W., Kunde, W., & Pfister, R. (2021). Temporal binding as multisensory integration: Manipulating perceptual certainty of actions and their effects. *Attention, Perception, & Psychophysics*, *83*(8), 3135–3145. https://doi.org/10.3758/s13414-021-02314-0

Krumpal, I. (2013). Determinants of social desirability bias in sensitive surveys: A literature review. *Quality & Quantity*, *47*(4), 2025–2047. https://doi.org/10.1007/s11135-011-9640-9

Kühn, S., Elsner, B., Prinz, W., & Brass, M. (2009). Busy doing nothing: Evidence for nonaction-effect binding. *Psychonomic Bulletin & Review*, *16*(3), 542–549. https://doi.org/10.3758/PBR.16.3.542

Loehr, J. D. (2022). The sense of agency in joint action: An integrative review. *Psychonomic Bulletin & Review*, *29*(4), 1089–1117. https://doi.org/10.3758/s13423-021-02051-3

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*(4), 476–490. https://doi.org/10.3758/BF03210951

Majchrowicz, B., & Wierzchoń, M. (2018). Unexpected action outcomes produce enhanced temporal binding but diminished judgement of agency. *Consciousness and Cognition*, *65*, 310–324. https://doi.org/10.1016/j.concog.2018.09.007

Melcher, T., Pfister, R., Busmann, M., Schlüter, M.-C., Leyhe, T., & Gruber, O. (2015). Functional characteristics of control adaptation in intermodal sensory processing. *Brain and Cognition*, *96*, 43–55. https://doi.org/10.1016/j.bandc.2015.03.003

Metcalfe, J., Eich, T. S., & Miele, D. B. (2013). Metacognition of agency: Proximal action and distal outcome. *Experimental Brain Research*, *229*(3), 485–496. https://doi.org/10.1007/s00221-012-3371-6

Mifsud, N. G., Beesley, T., Watson, T. L., & Whitford, T. J. (2016). Attenuation of auditory evoked potentials for hand and eye-initiated sounds. *Biological Psychology*, *120*, 61–68. https://doi.org/10.1016/j.biopsycho.2016.08.011

Moore, J. W. (2016). What is the sense of agency and why does it matter? *Frontiers in Psychology*, *7*, 1272. https://doi.org/10.3389/fpsyg.2016.01272

Moore, J. W., & Fletcher, P. C. (2012). Sense of agency in health and disease: A review of cue integration approaches. *Consciousness and Cognition*, *21*(1), 59–68. APA PsycInfo. https://doi.org/10.1016/j.concog.2011.08.010

Moore, J. W., & Haggard, P. (2008). Awareness of action: Inference and prediction. *Consciousness and Cognition*, *17*(1), 136–144. https://doi.org/10.1016/j.concog.2006.12.004

Moore, J. W., Lagnado, D., Deal, D. C., & Haggard, P. (2009). Feelings of control: Contingency determines experience of action. *Cognition*, *110*(2), 279–283. https://doi.org/10.1016/j.cognition.2008.11.006

Moore, J. W., & Obhi, S. S. (2012). Intentional binding and the sense of agency: A review. *Consciousness and Cognition*, *21*(1), 546–561. https://doi.org/10.1016/j.concog.2011.12.002

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, *215*(5109), 1519–1520. https://doi.org/10.1038/2151519a0

Notebaert, W., Houtman, F., Van Opstal, F., Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: An orienting account. *Cognition*, *111*(2), 275–279. https://doi.org/10.1016/j.cognition.2009.02.002

Oberauer, K. (2022). The importance of random slopes in mixed models for bayesian hypothesis testing. *Psychological Science*, *33*(4), 648–665. https://doi.org/10.1177/09567976211046884

Pacherie, E. (2014). How does it feel to act together? *Phenomenology and the Cognitive Sciences*, *13*(1), 25–46. https://doi.org/10.1007/s11097-013-9329-8

Penton, T., Wang, X., Coll, M.-P., Catmur, C., & Bird, G. (2018). The influence of action–outcome contingency on motivation from control. *Experimental Brain Research*, *236*(12), 3239–3249. https://doi.org/10.1007/s00221-018-5374-4

Pfister, R., & Foerster, A. (2022). How to measure post-error slowing: The case of pre-error speeding. *Behavior Research Methods*, *54*(1), 435–443. https://doi.org/10.3758/s13428-021-01631-4

Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology*, *9*(2), 74. https://doi.org/10.5709/acp-0133-x

Pfister, R., Weller, L., & Kunde, W. (2020). When actions go awry: Monitoring partner errors and machine malfunctions. *Journal of Experimental Psychology: General*, *149*(9), 1778–1787. https://doi.org/10.1037/xge0000748

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019

Reis, M., Pfister, R., & Schwarz, K. A. (2023). The value of control. *Journal of Behavioral Decision Making*. https://doi.org/10.1002/bdm.2325

Rescorla, R. A. (1967). Pavlovian conditioning and its proper control procedures. *Psychological Review*, *74*(1), 71. https://doi.org/10.1037/h0024109

Rescorla, R. A., & Wagner, A. (1972). A theory of Pavlovian conditioning: The effectiveness of reinforcement and non-reinforcement. *Classical Conditioning: Current Research and Theory*.

Rochat, P., & Striano, T. (1999). Emerging self-exploration by 2-month-old infants. *Developmental Science*, *2*(2), 206–218. https://doi.org/10.1111/1467-7687.00069

RStudio. (2020). *RStudio: Integrated Development Environment for R*. RStudio, PBC. http://www.rstudio.com/

Sato, A., & Yasuda, A. (2005). Illusion of sense of self-agency: Discrepancy between the predicted and actual sensory consequences of actions modulates the sense of self-agency, but not the sense of self-ownership. *Cognition*, *94*(3), 241–255. https://doi.org/10.1016/j.cognition.2004.04.003

Saunders, B., & Jentzsch, I. (2012). False external feedback modulates posterror slowing and the f-P300: Implications for theories of posterror adjustment. *Psychonomic Bulletin & Review*, *19*(6), 1210–1216. https://doi.org/10.3758/s13423-012-0314-y

Schneider, W. X., Albert, J., & Ritter, H. (2020). Enabling cognitive behavior of humans, animals, and machines: A situation model framework. *ZiF-Mitteilungen*, *1*, 21-34.

Schwarz, K. A., Klaffehn, A. L., Hauke-Forman, N., Muth, F. V., & Pfister, R. (2022). Never run a changing system: Action-effect contingency shapes prospective agency. *Cognition*, *229*, 105250. https://doi.org/10.1016/j.cognition.2022.105250

Schwarz, K. A., Tonn, S., Büttner, J., Kunde, W., & Pfister, R. (2023). Sense of agency in social hierarchies. *Journal of Experimental Psychology: General*, *152*(10), 2957–2976. https://doi.org/10.1037/xge0001426

Schwarz, K. A., & Weller, L. (2023). Distracted to a fault: Attention, actions, and time perception. *Attention, Perception, & Psychophysics*, *85*(2), 301–314. https://doi.org/10.3758/s13414-022-02632-x

Schwarz, K. A., Weller, L., Klaffehn, A. L., & Pfister, R. (2019). The effects of action choice on temporal binding, agency ratings, and their correlation. *Consciousness and cognition*, *75*, 102807. https://doi.org/10.1016/j.concog.2019.102807

Shanks, D. R., & Dickinson, A. (1991). Instrumental judgment and performance under variations in action-outcome contingency and contiguity. *Memory & Cognition*, *19*(4), 353–360. https://doi.org/10.3758/bf03197139

Sidarus, N., Vuorre, M., & Haggard, P. (2017). Integrating prospective and retrospective cues to the sense of agency: A multi-study investigation. *Neuroscience of Consciousness*, *2017*(1). https://doi.org/10.1093/nc/nix012

Siebertz, M., & Jansen, P. (2022). Diverging implicit measurement of sense of agency using interval estimation and Libet clock. *Consciousness and Cognition*, *99*, 103287. https://doi.org/10.1016/j.concog.2022.103287

Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition*, *17*, 219–239. https://doi.org/10.1016/j.concog.2007.03.010

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, *135*(2), 77–99. https://doi.org/10.1016/j.actpsy.2010.02.006

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, *5*(4), 297–323. https://doi.org/10.1007/BF00122574

van der Weiden, A., Aarts, H., & Ruys, K. I. (2011). Prime and probability: Causal knowledge affects inferential and predictive effects on self-agency experiences. *Consciousness and Cognition*, *20*(4), 1865–1871. https://doi.org/10.1016/j.concog.2011.09.007

van der Wel, R. P. R. D. (2015). Me and we: Metacognition and performance evaluation of joint actions. *Cognition*. https://doi.org/10.1016/j.cognition.2015.03.011

van der Wel, R. P. R. D., & Knoblich, G. (2013). Cues to agency: Time can tell. *Agency and Joint Attention*, *54*, 256. https://doi.org/10.1093/acprof:oso/9780199988341.003.0016

van der Wel, R. P. R. D., Sebanz, N., & Knoblich, G. (2012). The sense of agency during skill learning in individuals and dyads. *Consciousness and Cognition*, *21*(3), 1267–1279. https://doi.org/10.1016/j.concog.2012.04.001

Verleger, R., Grauhan, N., & Śmigasiewicz, K. (2016). Effects of response delays and of unknown stimulus-response mappings on the oddball effect on P3. *Psychophysiology*, *53*(12), 1858–1869. https://doi.org/10.1111/psyp.12756

Villa, R., Tidoni, E., Porciello, G., & Aglioti, S. M. (2020). Freedom to act enhances the sense of agency, while movement and goal-related prediction errors reduce it. *Psychological Research*. https://doi.org/10.1007/s00426-020-01319-y

Watson, J. S. (1985). Contingency perception in early social development. In T. M. Field & N. A. Fox (Eds.), Social perception in infants (pp. 157-176). Ablex.

Watson, J. S. (1997). Contingency and its two indices within conditional probability analysis. *The Behavior Analyst*, *20*(2), 129–140. https://doi.org/10.1007/BF03392770

Wegner, D. M. (2004). Précis of the illusion of conscious will. *Behavioral and Brain Sciences*, *27*(5), 649–659. https://doi.org/10.1017/S0140525X04000159

Wegner, D. M., & Wheatley, T. (1999). Apparent mental causation. Sources of the experience of will. *American Psychologist*, *54*(7), 480–492. https://doi.org/10.1037//0003-066x.54.7.480

Weller, L., Kunde, W., & Pfister, R. (2017). Non-action effect binding: A critical re-assessment. *Acta Psychologica*, *180*, 137-146. https://doi.org/10.1016/j.actpsy.2017.09.001

Weller, L., Schwarz, K. A., Kunde, W., & Pfister, R. (2020). Something from nothing: Agency for deliberate nonactions. *Cognition*, *196*, 104136. https://doi.org/10.1016/j.cognition.2019.104136

Wessel, J. R. (2018). Prepotent motor activity and inhibitory control demands in different variants of the go/no-go paradigm. *Psychophysiology*, *55*(3), e12871. https://doi.org/10.1111/psyp.12871

Wolpert, D. M., & Miall, R. C. (1996). Forward models for physiological motor control. *Neural Networks*, *9*(8), 1265–1279. https://doi.org/10.1016/s0893-6080(96)00035-4

Yon, D., & Press, C. (2017). Predicted action consequences are perceptually facilitated before cancellation. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(6), 1073–1083. https://doi.org/10.1037/xhp0000385