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Never run a changing system: Action-effect contingency shapes prospective agency

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ABSTRACT

Human action control is highly sensitive to action-effect contingencies in the agent's environment. Here we show that the subjective sense of agency (SoA) contributes to this sensitivity as a subjective counterpart to instrumental action decisions. Participants ($N = 556$) experienced varying reward probabilities and were prompted to give summary evaluations of their SoA after a series of action-effect episodes. Results first revealed a quadratic relation of contingency and SoA, driven by a disproportionally strong impact of perfect action-effect contingencies. In addition to this strong situational determinant of SoA, we observed small but reliable interindividual differences as a function of gender, assertiveness, and neuroticism that applied especially at imperfect action-effect contingencies. Crucially, SoA not only reflected the reward structure of the environment but was also associated with the agent's future action decisions across situational and personal factors. These findings call for a paradigm shift in research on perceived agency, away from the retrospective assessment of single behavioral episodes and towards a prospective view that draws on statistical regularities of an agent's environment.

1. Introduction

Goal-directed behavior draws on learned contingencies between one's own actions and changes in the environment, a mental faculty that is deeply rooted in the human brain (Gergely & Watson, 1999; Tarabulsy, Tessier, & Kappas, 1996). Following the critical role of contingency detection for adaptive behavioral choices, previous research has delineated how agents represent causal action-effect relations, and how they update these representations in changing environments (Behrens, Woolrich, Walton, & Rushworth, 2007; Hoffmann, 2003; Rescorla & Wagner, 1972; Wasserman, Elek, Chatlosh, & Baker, 1993). Not surprisingly, this line of research has focused on assessing how closely judgements and behavior mirror statistical properties of the environment. It is surprising, however, that the agent's subjective experience of controlling the events in question – their sense of agency (SoA) – has not been assessed in this context. That is, whereas SoA has been argued to rely on action-effect contingency, experimental work on this question has focused primarily on specific instances of action-effect contingency (e.g., Di Costa, Théro, Chambon, & Haggard, 2018; Moore, Lagnado, Deal, & Haggard, 2009; Nickels, Cramer, & Nantais-Therrien, 2018; van der Weiden, Aarts, & Ruys, 2011; see Liljeholm, 2021 for a theoretical discussion of this question) with a substantial part of these studies utilizing temporal binding as their SoA measure whose association to SoA has been discussed very controversially in recent years (Antusch, Custers, Marien, & Aarts, 2020; Klaffehn, Sellmann, Kirsch, Kunde, & Pfister, 2021; Majchrowicz & Wierzchoń, 2018; Reddy, 2021; Schwarz, Weller, Klaffehn, & Pfister, 2019; Siebertz & Jansen, 2022; Tonn, Pfister, Klaffehn, Weller, & Schwarz, 2021). To our knowledge, explicit SoA has never been studied with various, systematically changing action-effect contingencies, thus specifically designed to study SoA formation in a dynamic environment.

Moreover, previous observations on SoA revolve around single behavioral episodes to establish which factors promote agency over a specific action outcome (Chambon & Haggard, 2012; Chambon, Sidarus, & Haggard, 2014; Hughes, Desantis, & Waszak, 2013; Schwarz, Burger, Dignath, Kunde, & Pfister, 2018; Synofzik, Vosgerau, & Newen, 2008; Synofzik, Vosgerau, & Voss, 2013; Wegner & Wheatley, 1999; Wegner, 2003, but see Moore & Haggard, 2008, for a rare exception). Here we argue that bridging these two fields of research holds particular promise. For one, considering SoA as a subjective counterpart to statistical

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knowledge about action-effect relations can explain why agents sometimes do not base their action choices on knowledge about current action-effect contingencies. For another, bridging these fields allows for novel theorizing on the functional relevance of SoA.

Current consensus highlights SoA as a critical precursor to a sense of responsibility for action outcomes and as a means to enable self-other distinctions (Bigenwald & Chambon, 2019; Frith, 2014; Gallagher, 2000; Haggard, 2017; Haggard & Tsakiris, 2009; Rochat & Striano, 1999). These downstream consequences of SoA are only relevant if they feed into future actions. A main purpose of SoA therefore has to be a role in motivating future actions (e.g., Gozli, 2019; Gozli & Dolcini, 2018). Assessing its role for future actions, however, requires a paradigm shift from isolated behavioral instances towards SoA as a summary evaluation, jointly affected by both, situational and inter-individual factors (Tapal, Oren, Dar, & Eitam, 2017). In the current study, we start on this path by first evaluating and identifying situational and individual aspects affecting such SoA summary scores, and by then relating SoA to future action decisions.

To this end, we developed a novel paradigm that elicits substantially variable levels of SoA across different situations while also allowing for inter-individual variability in selected situations. Our method of choice was a structured manipulation of action-effect contingency over set periods of time (Allan, 1993; Behrens et al., 2007; Wasserman et al., 1993; Watson, 1997). The experimental paradigm therefore consists of various blocks with differing action-effect contingencies (50%, 70%, 80%, 90%, 100%), in which participants were instructed to choose between two possible buttons to elicit a smiling emoticon (see Fig. 1). Twice per block, participants were asked to rate their sense of control over the action outcome as well as the predictability of the action outcome, providing SoA summary scores that can be probed for their impact on future action decisions within the same block. After completing the experimental paradigm, participants answered a battery of personality questionnaires (see Fig. 2). This approach allowed us to probe for a wide spectrum of personality constructs including broad dimensions of personality like the Big Five as well as traits with a direct conceptual relation to SoA: Persons high in agency, global self-esteem, and general self-efficacy, with a high internal locus of control, a high sense of positive agency, and a low sense of negative agency should show high SoA in the experimental paradigm. We probed for a possible impact of such individual factors on SoA formation in experimental situations differing in certainty, i.e., action-effect contingency.

The goal of the presented study is therefore (1) to evaluate SoA as a subjective counterpart to action-effect contingency learning, (2) to study the impact of individual factors as well as the interplay of situation and individual factors on SoA formation, and (3) to analyze the association of SoA with future action decisions.

We expected SoA to vary dynamically with the respective action-effect contingencies, but that individual factors also played a role in determining SoA. Here, specifically, we expected construct-related questionnaires (Agency, Global Self Esteem, General Self-Efficacy, Internal Locus of Control, and the Sense of Agency Scale) to be positively associated with experimental SoA scores (Tapal et al., 2017). All other questionnaires, as well as gender and age variables, were implemented for exploratory purposes (see Fig. 2A for a summary of questionnaire-related hypotheses). We further expected SoA to be associated with future action decisions. Finally, we included perceived predictability ratings in addition to perceived control ratings to evaluate whether both are conceptualized similarly by participants or whether they differ, in an exploratory comparison of both ratings.

2. Methods

The preregistration, data, and analyses files are available on the Open Science Framework (https://osf.io/t36kb and https://osf.io/dr72m/).

2.1. Participants

We recruited 556 participants via the international platform Prolific. Sample size was determined via a power analysis (pwr package in R) for small correlations of $r = 0.15$, two-tailed testing, $\alpha = 0.05$, and a power of $1\text{-}\beta = 0.90$, resulting in an optimal sample size of $N = 463$ participants, plus an additional 20% to account for possible drop-outs or exclusion due to poor data quality.

Of these participants, we excluded 65 individuals (11.7%) for the following reasons: in a post-experimental questionnaire, they stated not to have paid attention to the task ($n = 6$), reported difficulties in understanding the task due to language issues ($n = 2$), correctly guessed the purpose of the study ($n = 5$), failed to correctly answer control questions interspersed into the personality questionnaires ($n = 19$), or showed erratic behavior in the experimental paradigm, such as almost no variation in control ratings between the 50% contingency block and the 100% contingency block ($n = 33$). The remaining sample size of $N = 491$ retained a power of $1\text{-}\beta = 0.91$ given the aforementioned parameters. Sample size and major exclusion criteria were pre-determined in our preregistration; language problems, control questions, and guessing

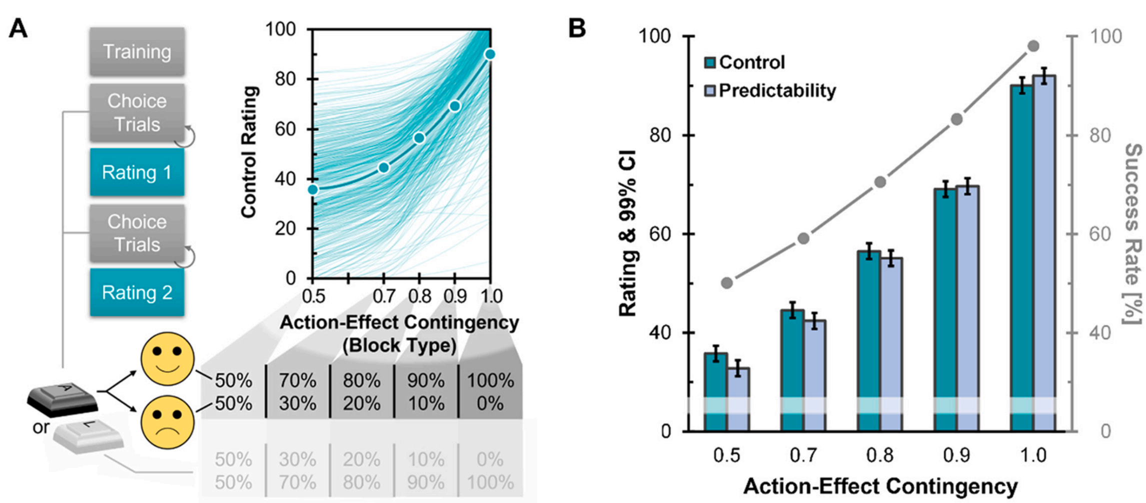

Fig. 1. Study design and central results. A. Individual control ratings as a function of action-effect contingency. Ratings followed a quadratic trend indicating that participants overly weighed perfect action-effect contingencies. B. Mean control and predictability ratings (bars) with 99% within-subjects confidence intervals (Loftus & Masson, 1994), as well as mean success rates (gray points) as a function of action-effect contingency.

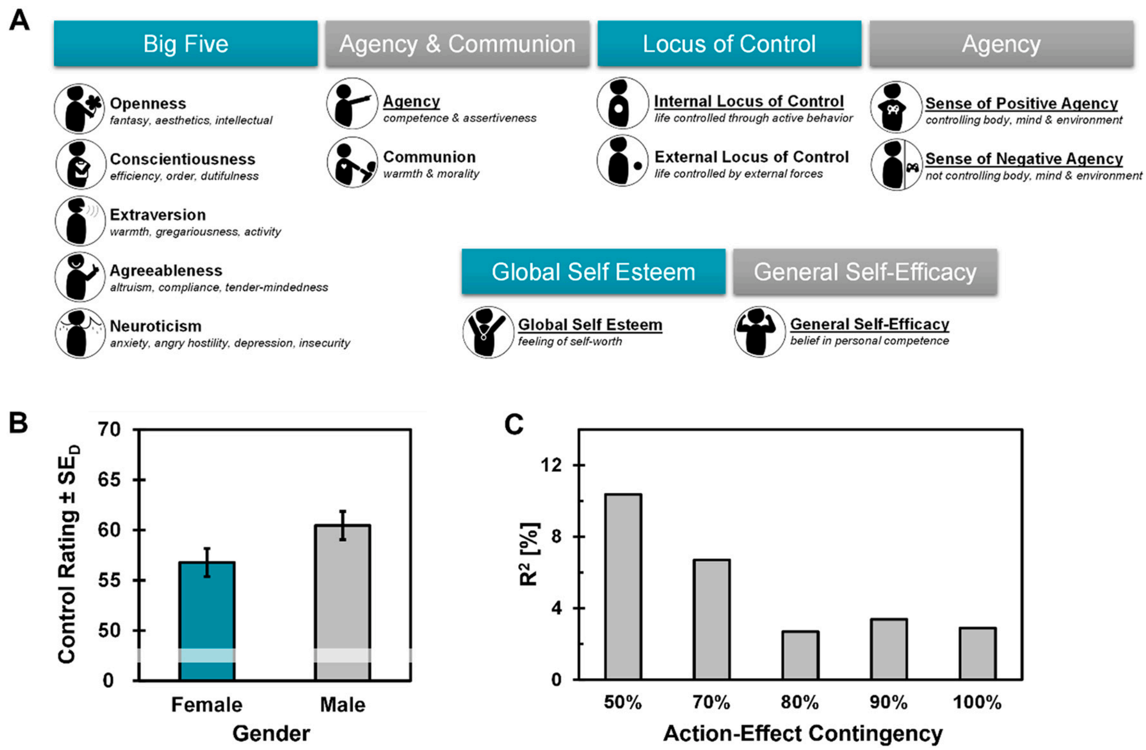

Fig. 2. A. Questionnaire battery including subscales where applicable. We employed the Big Five Inventory (John & Srivastava, 1999), the Agency-Communion-Inventory (Abele et al., 2016), the Short Scale for the Assessment of Locus of Control (Jakoby & Jacob, 1999; Kovaleva, 2012), the Sense of Agency Scale (Tapal et al., 2017), the Self-Esteem Scale (Rosenberg, 1965) and the General Self-Efficacy Scale (Bosscher & Smit, 1998). Underlined (sub)scales were expected to correlate with the feeling of control in the experimental paradigm. B. Gender identity, as an individual trait, affected control ratings significantly, $t(460) = 2.63$, $p = .009$, $d = 0.27$. Error bars depict the standard error of the difference between groups (SE_D). C. Explained variance [R^2] of the best-fitting model predicting control ratings by individual traits as a function of action-effect contingency. Individual traits contributed most to the prediction of control ratings in situations of highest uncertainty.

of the correct purpose were added later-on as additional exclusion criteria to preserve optimal data quality. Mean age of the remaining sample of 491 participants was 28.9 years ($SD = 10.5$, range 18–70) with 320 identifying as male, 142 female, and 3 as non-binary (26 participants chose not to answer the question). 412 identified as right-handed, 68 as left-handed, and as 10 ambidextrous (1 participant chose not to answer the question). Participants reported a total of 44 nationalities, the most common of which were the UK (n = 106), Poland (n = 99), Portugal (n = 47), Italy (n = 41), and USA (n = 36).

Participants gave informed consent prior to the experiment and received monetary compensation for participation.

2.2. Apparatus

The experiment was set up to be run in the browser of participants' home computer using the JavaScript library jsPsych (de Leeuw, 2015). The program was provided to the participants via a private server. The users' end device was required to have a physical keyboard but other than that, we had no control and gave no instructions on screen size, viewing distance or true stimulus size. The browser window was set to full screen upon the start of the experiment.

2.3. Procedure

At the beginning of the experiment, participants received a short introduction, asking them to produce as many happy faces as possible during the experimental blocks by pressing the keys A and L with their left and right index finger, respectively, and to rate their perceived control (i.e., SoA) when prompted. Participants were encouraged to respond quickly although no time limit was imposed on individual trials. Each trial started with a cue prompting participants to press one of the two keys, eliciting either a smiling or a frowning emoticon after a short delay of 100 ms. The emoticons only differed in the curvature of the mouth and were presented for 400 ms, followed by a 200 ms inter-trial interval. Each block started with 15 training trials to familiarize the participants with the keys' contingencies and participants were informed afterwards that the "real" block would commence. Blocks consisted of 50 trials and participants were asked to rate their perceived control as well as the predictability of the emotion of the face twice per block, once after half of the block and once at the end. The wording of the former question was "How much in control did you feel over the emotion of the face [during the current block (1st block half) / since the last rating (2nd block half)]?" whereas the latter question read "How predictable was the emotion of the face to you [during the current block (1st block half) / since the last rating (2nd block half)]?". The scales ranged from 0 (no control, not predictable) to 100 (full control, perfectly predictable). Blocks differed in contingency levels (50%, 70%, 80%, 90%, 100%; contingency levels were chosen based on pilot studies), and participants underwent each contingency condition twice, resulting in 10 experimental blocks. Block order was randomized. The key-outcome mapping was randomized between different contingency conditions but remained the same for blocks of the same contingency condition.

After completing the experimental paradigm, participants went through six personality questionnaires in English in a fixed order (for details see Fig. 2, and the Supplementary Material), two of which contained control questions with clearly correct and incorrect answers, to evaluate the individual participant's attention to the questions. Finally, participants were queried about study details as well as the quality of their own data regarding effort and paid attention. These questions were clearly marked as not incurring any repercussions in case of negative responses. Participants then automatically received their payment.

2.4. Data analysis

2.4.1. Situational aspects

We analyzed control ratings and predictability ratings in separate repeated-measures analyses of variance (ANOVAs) with the factor action-effect contingency (50% vs. 70% vs. 80% vs. 90% vs. 100%). These ANOVAs were followed-up by two-tailed paired *t*-tests for pairwise comparisons, with corresponding effect sizes being calculated as $d_z = \frac{t}{\sqrt{n}}$. We also computed bivariate correlations between predictability and control ratings to gauge their association.

Linear and quadratic models for control and predictability ratings were tested via mixed effects models in R (lmer package) with contingency as fixed factor and subject as random effect. For both ratings we fit separate models for linear and quadratic coding of contingency and extracted the variance explained for each model (marginal and conditional R^2 as computed with the MuMIn package). For the quadratic trend, we further subtracted 0.5 from the contingency levels, as the contingency 50% (i.e., 0.5) serves as our control minimum and should therefore coincide with the minimum for the quadratic curve.

To analyze the relationship of nominal contingency, i.e., actual control, and success rates, i.e., experienced success, as a manipulation check, we first computed regression analyses with the predictor contingency and the criterion of success rate separately for each participant to gain individual slope values, as well as regression analysis across all participants to calculate R^2. We then analyzed differences in actual values by computing an ANOVA with the factors blocktype and control (actual vs. experienced) with contingency levels serving as an index for actual control and the participants' success rates as experienced success, followed-up by two-tailed paired *t*-tests for pairwise comparisons.

2.4.2. Individual aspects

All personality scales came with satisfactory reliability, Cronbach's $\alpha > 0.70$ (see Supplementary Table 1), with the sole exception of the "locus of control" scale whose interpretation therefore has to be taken with caution.

Primary analyses for all individual aspects included mean control ratings and control slopes as SoA measures. More precisely, mean control ratings were employed to measure different SoA levels in individuals, whereas control slopes were intended as a measure of sensitivity to different situational contingencies. As such, control slopes were calculated via a regression analysis with the predictor contingency and the criterion control ratings, separately for each subject. As the quadratic model fit the control ratings best, we added the predictor contingency with squared values (i.e., (contingency-0.5)^2; the subtraction of 0.5 allows the 50% condition to serve as the minimum of the quadratic curve) to allow for a quadratic model. The steeper the resulting slope, the higher the change in control ratings between lower and higher contingencies, positive slopes indicate a positive relationship of contingency and control (i.e., the higher the contingency, the higher the control rating), whereas negative slopes would indicate the opposite. As erratic rating behavior was an exclusion criterion (i.e., less reported control in 100% contingency block than in 50% contingency blocks), all slope values included in the analyses were positive.

To probe for the relationship of gender and SoA scores, we computed a *t*-test for independent samples between individuals identifying as male and individuals identifying as female for both, mean control ratings and control slopes. To analyze the relationship of age and personality trait scores with SoA, we correlated all measured personality constructs and age with both, mean control ratings, and control slopes. Please note that for all analyses including the gender variable, we excluded all individuals that reported either as "diverse", as this group was too small for meaningful statistical analysis, or chose not to report their gender at all. This decreases sample size for these analyses to $n = 462$, still resulting in a power of $1\text{-}\beta = 0.90$, given the aforementioned parameters of the power analysis (see Methods).

As a control analysis, we calculated success-control slopes via regression analysis with the predictor success rates and the criterion control ratings, separately for each subject. The resulting slope values were then correlated with the measured personality constructs as well as age to evaluate whether previous results were mainly driven by the difference between actual control (i.e., contingencies) or experienced success (i.e., success rates).

2.4.3. The interaction of situational and individual aspects

We first calculated linear mixed-effect models, including control ratings as the criterion and contingency as the first predictor; as the quadratic model fitted the control ratings best, we added the predictor contingency with squared values (i.e., (contingency-0.5)^2; the subtraction of 0.5 allows the 50% condition to serve as the minimum of the quadratic curve) to allow for a quadratic model. We then expanded the equation step-wise by including first gender and then all measured personality traits as well as age and interactions of these individual factors with contingency as the situational factor. Inclusion was ordered according to the correlational value to SoA scores the previous analyses had ascribed to the respective individual measure. Only those individual factors remained in the equation that contributed significantly to model fit, either on their own or in the interaction term with contingency.

To analyze whether individual factors affect SoA scores differently in different situations, we calculated follow-up multiple regression analyses separately for each contingency level with the criterion control ratings. All measured personality traits as well as gender and age were entered into a step-wise regression, to assess the best fitting model for each contingency level.

2.4.4. Prospective agency

To evaluate the impact of SoA on future action decisions, we first calculated a regression analysis with the predictor SoA ratings of the first block half and the criterion success rate of the second block half as an indicator of subsequent action choice, separately for each contingency level. For the impact of SoA on the immediate key press after the rating, we similarly regressed SoA ratings of the first block half on the correct key rate for the first keypress in the second half of the block. As a control for the level of experience with the situation, we additionally calculated a regression slope analysis, by first calculating a regression with the predictor success rate (1st half of the block) and the criterion success rate (2nd half of the block), separately for each participant, to control for the level of success in the respective contingency block. We then calculated a regression analysis with the predictor agency ratings (1st half of the block) and the slope of the previous regression, i.e., the change in success between the first and the second half or the block, as the criterion. To ensure that experience does not single-handedly explain the association of SoA and success rates in the second half, we additionally calculated analyses of regression residuals after regressing out the impact of actual success rates. To this end, we first calculated a regression analysis using success rates of the first block half as predictors and success rates of the second block half as criterion. The difference between the observed and predicted data pattern is represented in the resulting residuals, and these residuals are then used as the criterion in a second regression analysis with control ratings of the first block half as the predictor.

Table 1
Mean ratings of participants' control ($M_{Control}$) and predictability ($M_{Predict}$).

Contingency	$M_{Control}$	Pairwise comparisons	$M_{Predict}$	Pairwise comparisons
50%	35.78		32.80	$50\%_{Control}$ vs $50\%_{Predictability}$: $t(490) = 7.29, p < .001, d_z = 0.33$
70%	44.58	$50\%_{Control}$ vs $70\%_{Control}$: $t(490) = 12.10, p < .001, d_z = 0.55$	42.41	$70\%_{Control}$ vs $70\%_{Predictability}$: $t(490) = 5.24, p < .001, d_z = 0.24$
80%	56.53	$70\%_{Control}$ vs $80\%_{Control}$: $t(490) = 16.79, p < .001, d_z = 0.76$	55.12	$80\%_{Control}$ vs $80\%_{Predictability}$: $t(490) = 3.20, p = .001, d_z = 0.14$
90%	69.13	$80\%_{Control}$ vs $90\%_{Control}$: $t(490) = 16.95, p < .001, d_z = 0.76$	69.73	$90\%_{Control}$ vs $90\%_{Predictability}$: $t(490) = -1.29, p = .197, d_z = -0.06$
100%	90.01	$90\%_{Control}$ vs $100\%_{Control}$: $t(490) = 30.33, p < .001, d_z = 1.37$	91.98	$100\%_{Control}$ vs $100\%_{Predictability}$: $t(490) = -5.14, p < .001, d_z = -0.23$

3. Results

3.1. Situational aspects of SoA

Fig. 1 shows the main results relating to situational influences on SoA. As expected, action-effect contingency had a strong effect on perceived control (Table 1), $F(4,1960) = 1388.42$, $p < .001$, $\eta_p^2 = 0.74$, $\varepsilon = 0.87$ (GG-corrected). Interestingly, when control ratings were regressed on action-effect contingencies, the best fit was achieved by a quadratic model indicating that participants overly weighed perfect action-effect contingencies (Fig. 1A). A quadratic model captured 76.8% of the measured between-condition variance (conditional R^2) as compared to 71.0% for a linear model. This difference was mirrored in Bayesian Information Criteria (BIC) with with $BIC_{linear} - BIC_{quadratic} = 20{,}808.9–20{,}370.6 = 438.2$, with a relative likelihood of $\mathscr{L}_{relative} < 0.001$ for the linear to minimize information loss relative to the quadratic model. Predictability ratings mirror these findings (see the Supplementary Material); indeed perceived control and perceived predictability were highly correlated across participants, $r = 0.88$, $r^2 = 0.78$, $p < .001$. However, control ratings were systematically higher than predictability ratings, $M_{Control} = 59.21$, $M_{Predict} = 58.41$, $\Delta = 0.80$, $t(490) = 2.64$, $p = .009$, $d_z = 0.12$ (Fig. 1B). This effect was mainly driven by higher control than predictability ratings during highly uncertain situations, but this difference reverses for situations of high certainty, interaction *Ratingtype x Contingency*, $F(4,1960) = 38.83$, $p < .001$, $\eta_p^2 = 0.07$, $\varepsilon = 0.92$ (GG-corrected).

As participants can be expected to deviate from the mathematically optimal strategy to ensure a maximal success rate, we further analyzed how contingency levels and experienced success related to one another across different contingency blocks. Our results indicate that while participants' experienced success did correlate positively with actual control, not surprisingly, participants did not reach the optimal possible success rate and experienced success was consistently lower than contingency levels. For the following correlational analyses, we therefore included control analyses of success rates instead of the actual contingencies to assure that observed correlations are not driven by this difference between experienced success and actual control (for details regarding these results, see the Supplementary Material).

3.2. Individual aspects of SoA

Standard deviations of the measured personality traits ranged from 0.50 to 0.93, suggesting a reasonably broad spectrum in personality scores for five-point scales as used in this experiment (see Supplementary Table 1 for complete descriptive statistics).

For individual aspects of agency, we first tested how age and gender relate to SoA. Mean control ratings differed between individuals identifying as male and female, with male participants rating their perceived control generally higher than female participants, $M_{male} = 60.45$, $M_{female} = 56.77$, $\Delta = 3.68$, $t(460) = 2.63$, $p = .009$, $d = 0.27$ (Fig. 2B). As a measure of SoA adaptation across different contingencies, we calculated control slopes (control scores regressed on contingencies; higher slope values indicate more change in control ratings between lower contingencies and higher contingencies) and tested the difference between male and female individuals which remained not significant, $|t| < 1$, $p > .736$. The correlation between age and mean control ratings was only marginally significant, $r = -0.08$, $p = .067$, and the correlation of age and control slopes remained not significant, $r = -0.06$, $p = .177$. These results indicate that gender identity affects SoA levels, but it does not affect the change of SoA due to situational contingencies. Age, on the other hand, seems to have little effect on SoA scores in general.

In a next step, we calculated correlational analyses for all measured personality traits and both, control ratings and control slopes, as main SoA measures (see Supplementary Table 2 for statistical parameters for all correlations). Please note that both SoA measures are negatively correlated, $r = -0.24$, $r^2 = 0.06$, $p < .001$. A possible explanation for this relationship is due to ceiling effects: if participants rate their control high even in uncertain situations, i.e., 50% contingency blocks, leading to an overall high control rating it cannot increase for certain situations as much as it can for participants who rate their control lower in uncertain situations and have therefore an overall lower control rating. Nevertheless, the resulting correlation is still small to medium-sized with only 6% of the measured variance explained, rendering separate correlational analyses for both measures suitable.

The participants' SoA level was predominantly affected by Neuroticism, $r = -0.13$, $r^2 = 0.02$, $p = .005$ and Openness, $r = 0.12$, $r^2 = 0.01$, $p = .011$ (for a summary of all personality traits associated with measures of SoA, see Supplementary Table 2). Moreover, mean control ratings also correlated positively to the positive SoA trait construct, $r = 0.18$, $r^2 = 0.03$, $p < .001$. Aside from the construct Neuroticism, all significant correlations were positive, indicating that more pronounced trait variables were associated with higher control ratings. The participants' change in SoA ratings dependent on situational contingencies, i.e. control slopes, were predominantly affected by the Agency subscale Assertiveness, $r = -0.18$, $r^2 = 0.03$, $p < .001$, Self-Esteem, $r = -0.14$, $r^2 = 0.02$, $p = .002$, and Neuroticism, $r = 0.14$, $r^2 = 0.02$, $p = .002$. Control slopes were also negatively correlated to the positive, $r = -0.11$, $r^2 = 0.01$, $p = .012$, and negative SoA trait construct, $r = -0.14$, $r^2 = 0.02$, $p = .002$. Aside from the construct Neuroticism, all significant correlations were negative, indicating that more pronounced trait variables were associated with less change in SoA scores dependent on situational contingencies. All found correlations were rather small with the individually explained variances ranging from 1% to 3%. Control analyses including slopes that were computed by regressing control ratings on success rates rather than contingencies, i.e. experienced success instead of actual control, mirror these results (see Supplementary Results and Supplementary Table 3).

3.3. Interaction of individual and situational aspects

To evaluate how situational and individual aspects of SoA interact, we fit a linear mixed-effects model with the criterion control ratings and all measured personality traits as well as gender and age as predictors (for constructs with subscale, we opted to include the subscales rather than the overall construct; for a correlation matrix of all personality constructs, please see Supplementary Table 4). These predictors were integrated step-wise into the model including interaction terms of the respective predictor with contingency; inclusion was ordered according to the strength of previously calculated correlations with SoA scores. Only those predictors or interactive terms remained whose inclusion significantly improved the model, resulting in the following term (for statistical details see Supplementary Table 5):

$$\text{control ratings} \sim \text{contingency} + \text{gender} + \text{SoA.positive} + \text{SoA.positive}^{*}\text{contingency} + \text{Agency.Assertiveness} + \text{Agency.Assertiveness}^{*}\text{contingency} + \text{SoA.negative} + \text{SoA.negative}^{*}\text{contingency} + \text{Communion.Morality} + \text{Communion.Morality}^{*}\text{contingency} + (1|\text{subject})$$

Of the included predictors, Agency.Assertiveness, SoA.negative, and Communion.Morality contributed to the model only in their interaction with contingency indicating that their contribution is dependent on situational factors. After inclusion of all factors, the complete model explained 76.33% of the measured variance (conditional R^2) and the fixed factors explained 54.18% of the measured variance (marginal R^2). In contrast, the model only including contingency as a fixed factor [control ratings ~ contingency + (1|subject)] explained 75.52% of the measured variance (conditional R^2), with contingency accounting for 52.18% of that variance (marginal R^2). A statistical comparison of both models reveals that, despite the small change in explained variance, the inclusion of these individual measures significantly improved model quality, $X^2(9) = 85.89$, $p < .001$; $BIC_{contingency} = 19{,}238.0$, $BIC_{complete} = 19{,}191.9$, with a relative likelihood of $\mathscr{L}_{relative} < 0.001$ for the contingency-only model to minimize information loss relative to the complete model. Please note that differences to previously reported values to similar analyses stem from the exclusion of all participants not identifying as either male or female for this analysis (see Methods).

As several individual factors only contributed to the model in interactive terms with the situational factor contingency, we followed up this analysis with multiple regression analyses separately calculated for each contingency level to evaluate which individual factors may play a role in which situation, and in which situations individual factors may play a stronger role than in others (Fig. 2C; Supplementary Table 6). The most variance was explained by individual factors at the 50% contingency level, control ratings ~ SoA.positive + SoA.negative + Neuroticism + Communion.Morality + Openness + Agreeableness, $r = 0.32$, $r^2 = 0.10$.

3.4. Prospective agency

In a last step, we analyzed if and when SoA is associated with future action decisions. To this end, we regressed success rates of the second part of each contingency block on SoA ratings of the first part of the block thus allowing us to analyze associations between SoA ratings and the subsequent action choices. Whereas SoA ratings did not predict future action choices in uncertain situations, i.e., 50% and 70% contingency blocks, they predicted subsequent action choices in higher certainty conditions with increasing accuracy, 80% block: $r = 0.16$, $r^2 = 2.5\%$, $F(1{,}489) = 12.67$, $p < .001$; 90% block: $r = 0.18$, $r^2 = 3.2\%$, $F(1{,}489) = 15.95$, $p < .001$; 100% block: $r = 0.32$, $r^2 = 10.2\%$, $F(1{,}489) = 55.45$, $p < .001$ (Fig. 3). A similar pattern emerged when we used SoA ratings of the first block halves to predict the immediate key press after the SoA rating, 90% block: $r = 0.15$, $r^2 = 2.3\%$, $F(1{,}489) = 11.62$, $p = .001$; 100% block: $r = 0.20$, $r^2 = 4.1\%$, $F(1, 489) = 20.85$, $p < .001$.

To ensure that these results were not merely driven by the participants' experience in the first half of the block, we performed two control analyses: First, we calculated a less biased criterion value for the analysis by conducting a regression analysis and using success rates (1st half) as predictor and success rates (2nd half) as criterion for each participant and then using the resulting regression slopes as the criterion in a further regression with the predictor SoA ratings (1st half). Even though this likely underestimates the association of SoA and action choices, as success rates represent the participants' experienced success, that association was still significant, $r = 0.20$, $r^2 = 3.9\%$, $F(1, 489) = 20.06$, $p < .001$. As a second control analysis, we used the residuals rather than the slopes of the aforementioned regression analysis as a criterion and the control ratings of the first block half as the predictor. Although, this is a very conservative approach, results indeed still show a significant

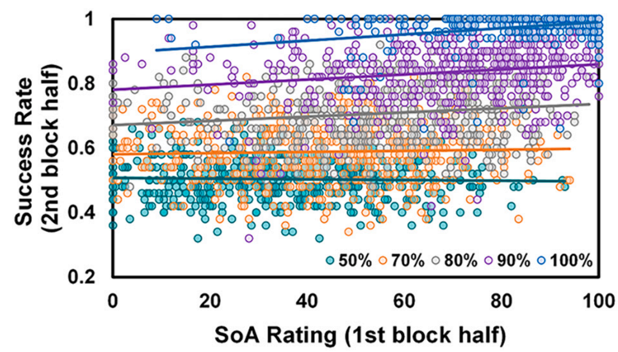

Fig. 3. Predicting future action choices, i.e., success rates in the second half of contingency blocks, with SoA ratings (first half of contingency blocks). Predictions were the more accurate, the higher the action-effect contingency, with up to 10.2% of explained variance in certain situations (100%) and no association in uncertain situations (50%).

association of SoA and subsequent behavior, $r = 0.04$, $F(1{,}2453) = 4.57$, $p = .037$, mainly due to a strong association of SoA and behavior in situations of complete control, $r = 0.20$, $F(1{,}2453) = 19.88$, $p < .001$.

Moreover, an explorative analysis comparing ratings in the first half of the experimental blocks with the ratings of the second half showed that ratings were generally slightly higher in the second half than in the first half, $F(1{,}490) = 6.44$, $p = .011$, $\eta_p^2 = 0.01$, but that this effect was situation-dependent, $F(4{,}1960) = 3.12$, $p = .014$, $\eta_p^2 = 0.01$, $\varepsilon = 0.92$ (GG-corrected). Post-hoc *t*-tests revealed that this effect was only significant for perfect action-effect contingencies (100% block), $M_{100,1st} = 88.80$, $M_{100,2nd} = 91.23$, $\Delta_{100,2nd\text{-}1st} = 2.42$, $t(490) = 5.89$, $p < .001$, $d_z = 0.27$. As participants underwent practice blocks before starting the experimental blocks and perfect action-effect contingencies are quickly and easily learned, this effect is unlikely to be based on learning effects – and indeed success rates do not differ between both block parts (across all contingency levels: $F(1{,}490) = 0.29$, $p = .590$; separately for all contingency levels: $ps > .220$).

4. Discussion

Human action control is highly sensitive to action-effect contingencies with predictive processes evaluating the likelihood of action outcomes (Behrens et al., 2007; Hoffmann, 2003; Wolpert, 1997; Wolpert, Ghahramani, & Jordan, 1995) and action choices at least partly depending on success probabilities (e.g., Castegnetti et al., 2020). In this study, we conceptualize sense of agency (SoA) as the subjective counterpart of this sensitivity, probing for its formation in situations of varying outcome uncertainty, and evaluating the influence of interindividual factors as well as interactive properties of situational and interindividual effects. Moreover, we take a first step in studying SoA not only as measure for specific past events, but characterize its impact on future action decisions. To this end, we asked 556 individuals to rate their sense of control related to their actions' outcome in a novel paradigm employing situations with 5 different levels of certainty of outcome (i.e., contingency levels). Afterwards, participants were asked to fill in a variety of personality questionnaires including broad dimensions of personality as well as traits with a direct conceptual relation to SoA.

Our results demonstrate that action-effect contingencies are closely related to subjective SoA, and while individual factors generally affect SoA formation only slightly, they play a significant role in situations of utmost outcome uncertainty. Moreover, our results show that SoA scores are significantly associated with future action choices, arguing for a conceptualization of SoA as a motivator for future voluntary actions (Di Costa et al., 2018; Eitam, Kennedy, & Higgins, 2013).

In an exploratory analysis, we further evaluated whether the perceived predictability of an action outcome is similarly or differently conceptualized to the perceived control over the outcome. Our results indicate that predictability and control seem to go hand-in-hand: the more predictable the action outcome, the more control the agent perceives over the action outcome. Thus, we could postulate that prediction is generally one of the most relevant factors involved in SoA formation (and, indeed, this is in line with many concepts of SoA; Blakemore, Frith, & Wolpert, 1999; Synofzik et al., 2008; Haggard and Tsakiris, 2009). However, this is not always the case. We can experience SoA even in situations in which we could not predict an action outcome, e.g., because we effected a change in the environment by accident: if we accidentally push a glass off a table, we can still state "I did push this glass", and "I had control over the glass" (just maybe not a good oversight over all objects and body parts in this scenario). A better conclusion thus might be that predictability seems to be a close sibling to SoA formation for voluntary actions in dynamic environments, but it is not a general necessity for SoA formation. Interestingly, predictability ratings were lower than control ratings in situations of little control (with the biggest difference for situations of no control, i.e., 50% contingency), and higher than control ratings in situations of absolute control (i.e., 100% contingency). Thus, although predictability ratings did not reach the possible extremes (0% and 100%), they accurately showed more variation depending on situational context, possibly indicating a more objective measure than perceived control. Note, however, that this result was not previously anticipated, and all interpretations are therefore post-hoc, and have to be taken with caution.

4.1. The situation and the individual

Action-effect contingencies explained most of the measured variance in SoA expressions, with contingency relating to control ratings best in a quadratic model fit hinting at an over-consideration of highly predictable action-effect contingencies. Individual factors only increased the explained variance by few points of percentage. Nevertheless, we identified several personality constructs correlated with SoA scores. SoA levels were most affected by gender identity, Neuroticism, and Openness, and the participants' change in SoA ratings across different situations being most affected by Assertiveness (Agency subscale), Self-Esteem, and Neuroticism. In actual values, Neuroticism as the only negative trait proved the outlier among these personality constructs as its relation to SoA scores always showed the opposite sign than the other positive trait variables, i.e., higher Neuroticism is associated with lower SoA levels and a steeper rise in control ratings across increasing contingencies. Of the interindividual factors significantly contributing to the prediction of SoA scores, Agency and Self-Esteem (as well as Self-Efficacy which contributed to a smaller degree) are related conceptually to SoA, and thus their relationship with SoA is unsurprising (e.g., Tapal et al., 2017). However, Neuroticism, Openness, and Extraversion are broad personality constructs not associated with SoA so far, rendering their association with perceived control an exciting, new find. Moreover, our data show for the first time that experimental measures of SoA which are by design strongly shaped by situational parameters, i.e., experimental manipulation, relate to trait conceptualizations of SoA (Tapal et al., 2017), although to a small degree.

Generally speaking, interindividual factors seem to play only a small role in SoA formation; however, when we look at the interactive properties of situational and interindividual factors, a different picture emerges. Several factors, such as the trait factor Assertiveness (Agency subscale), only contributed to SoA prediction via their interactive terms highlighting the relevance of situational features, and follow-up analyses revealed that individual factors explain a considerable amount of variance (up to 10%) in situations of highest uncertainty, i.e., low action-effect contingencies (50% and 70% conditions). Personality constructs contributing to the prediction model in these situations especially include the SoA trait construct, as well as Neuroticism, Openness, and Agreeableness. Morality (Communion subscale) is likely to function as a suppressor variable, having shown no correlation with control ratings on its own.

This finding is in line with previous accounts on the influence of personality traits on behavior. Classical research has formulated several prerequisites that allow interindividual factors to affect behavior dependent on the situational space for behavioral variance by postulating that individual factors can only affect overt behavior when behavioral variance is possible or likely (Buss, 1989; Mischel, 1977). This is the case, for instance, if participants have more freedom of choice and less precise instructions leading to more natural variance that can be affected by personality traits. Especially in the 50% contingency condition in the present study, each key held the same chance for a positive or negative outcome (i.e., 50%), and participants therefore had complete freedom of choice without breaking with the task goal (producing a smiling emoticon). Thus, the finding that individual factors predicted SoA scores best in the 50% contingency condition (and, to a slightly smaller degree, in the 70% condition) directly follows the logic of this argument.

4.2. Prospective agency

SoA ratings of the first half of the experimental blocks were significantly associated with action choices in the second half of the experimental blocks, measured either via success rates or the immediate key choice after the rating. Note that this relation even held true when we controlled for the level of success to limit the influence of previous experience on this effect, and an association of SoA and subsequent behavior remained significant even if success was excluded from the equation. However, it is important to stress that this does not mean that SoA or future action choices are independent from previous experiences; in fact, our results in this study emphasize that experiencing statistical regularities strongly impacts both, SoA ratings and behavior, to a point that SoA could even be argued to represent a subjective counterpart of perceived action-effect contingencies. This is further corroborated by the finding that the association of SoA ratings in the first block half and agentive behavior in the second block half is reduced when previous success (i.e., experience of statistical regularities) is mathematically excluded from the analysis. Nevertheless, these analyses indicate that the association of SoA ratings with future agentive behavior is genuine. Which mechanisms underlie this association seems a fruitful avenue for future research.

Interestingly, this association was true only in situations in which participants could draw on statistical regularities and therefore effecting at least some control over the action outcome. Having control over any effect can be rewarding in itself, resulting in faster reaction times for controllable than uncontrollable effects (Eitam et al., 2013). Additionally, the precision of the prediction of a specific effect seems to be deterministic for this mechanism which is not only reflected in action choice (as in the present experiment) but also in response times (Hemed, Bakbani-Elkayam, Teodorescu, Yona, & Eitam, 2020).That SoA does not affect future action choices (if measured in success rates as in this experiment) in situations without actual control is not surprising as it simply indicates that without actual control, participants have no means to affect future successes and therefore cannot make informed action choices. However, the gradual increase in association between SoA and future actions across different, increasing contingency levels could additionally indicate (1) that some level of SoA must be reached for it to affect future actions, or (2) that high SoA levels could be rewarding in themselves and additionally motivate participants to seek out correct key presses. Taken together, the present findings suggest that SoA contributes to future action choices and, in turn, that cumulative success in situations of high certainty increases SoA even further, even if success rates are stable over time.

4.3. Future directions

The current results emphasize the influence of statistical regularities, i.e., action-effect contingencies, on perceived control or SoA. However, the experiment can only draw conclusions regarding action-specific contingency (i.e., how likely is a specific outcome given a specific action?). Yet, in the classical definition, the degree of contingency is calculated as Delta-*p*: the difference between two probabilities, $\Delta p = p(E \mid R) - p(E \mid -R)$, i.e., the probability a specific action (response, R) was executed, given the effect (E) is present, minus the probability that no such action was performed, given the effect is present (Elsner & Hommel, 2004; Rescorla, 1967). In the current experimental design, the first half of this equation is clearly manipulated across different blocks, but the second half of the equation (i.e., the appearance of "effects" without an action) remains consistently zero. Exploring how the second half of this equation might affect the relationship between action-effect contingency and SoA would provide a very interesting first step as a continuation to the present study. Indeed, there are several accounts convincingly arguing that for a complete understanding of action-effect relation, SoA, and the perception of causation, even more factors need to be addressed, such as the Jensen-Shannon divergence or causal power (Chambon, Thero, Findling, & Koechlin, 2018; Cheng, 1997; Liljeholm, 2021).

5. Conclusions

Action-effect contingencies crucially affect SoA formation with a nonlinear, quadratic curve best explaining the relationship between contingency and control ratings, revealing the participants' tendency to overly weigh perfect action-effect associations. The contribution of interindividual differences was small overall, but their impact increased greatly in situations of utmost outcome uncertainty. Importantly, SoA was also associated with the agent's future action decisions in situations of higher outcome certainty, asserting its role in the choice of future actions.

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CRediT authorship contribution statement

K.A. Schwarz: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft. **A.L. Klaffehn:** Data curation, Investigation, Visualization, Writing – review & editing. **N. Hauke-Forman:** Data curation, Formal analysis, Methodology, Writing – review & editing. **F.V. Muth:** Data curation, Formal analysis, Writing – review & editing. **R. Pfister:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2022.105250.

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