Cognition 257 (2025) 106062

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

# Rational choices elicit stronger sense of agency in brain and behavior

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ARTICLE INFO

*Keywords:*
Sense of agency
Sense of control
Rationality
EEG
Event-related potentials

ABSTRACT

The sense of agency is the subjective feeling of control over one's own actions and the associated outcomes. Here, we asked whether and to what extent the reasons behind our choices (operationalized by value differences, expected utility, and counterfactual option sets) drive our sense of agency. We simultaneously tested these three dimensions during a novel value-based decision-making task while recording explicit (self-reported) and implicit (brain signals) measures of agency. Our results show that choices that are more reasonable also come with a stronger sense of agency: humans report higher levels of control over the outcomes of their actions if (1) they were able to choose between different option values compared to randomly picking between options of identical value, (2) their choices maximizes utility (compared to otherwise) and yields higher than expected utility, and (3) they realize that they have not missed out on hidden opportunities. EEG results showed supporting evidence for factors (1) and (3): We found a higher P300 amplitude for picking than choosing and a higher Late-Positive Component when participants realized they had missed out on possible but hidden opportunities. Together, these results suggest that human agency is not only driven by the goal-directedness of our actions but also by their perceived rationality.

## 1. Introduction

We don't just do things because we expect reward, but because we see reasons to do them – a feature which may be distinctive of humans (though see Tomasello, 2022 for an extension to primates). While it is disputed whether reasons are only post-hoc interpretations or actual determinants of our behavior (Cushman, 2020), they certainly shape the way we reflect and justify our decisions. Do they also shape the way we feel about, and reflect on, our agency?

The sense of agency (SoA) encompasses the feeling and judgment we have of choosing our actions and exercising control of these actions and their effects on the external environment (Bonicalzi & Haggard, 2019; Borhani et al., 2017). The sense of agency can be explored directly, by inquiring how much control individuals perceive they had over a specific result, or indirectly, by analyzing objective performance indicators (e.g., intentional binding, reaction times, sensory attenuation in self-touch (Pyasik et al., 2019)) and neurophysiological signatures linked to the processing of action outcomes (Beyer et al., 2017; Wen & Imamizu, 2022; Giersiepen et al., 2023).

Our perception of agency is often influenced by relevant features of the decision-making process: how easy it is to select an action (Chambon et al., 2014; Chambon & Haggard, 2012), how many options we are offered (Barlas & Obhi, 2013), whether we are coerced by an authority (Caspar et al., 2016), or share the task with other people (Beyer et al.,

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https://doi.org/10.1016/j.cognition.2025.106062
Received 23 May 2024; Received in revised form 20 December 2024; Accepted 6 January 2025
Available online 27 January 2025

2017; El Zein et al., 2022). We also tend to feel more in control when our choices achieve positive outcomes – something that reflects goal-directed agency but may also result from self-serving biases (Beyer et al., 2017) and connects to irrational illusions of control (Wegner, 2002). But could our sense of agency also depend on how much reason we see – or at least can see – for our choice?

Addressing the question of rational decisions is challenging due to diverse interpretations across disciplines. Rational choice theories emphasize maximizing preferences given information, while bounded rationality and ecological models stress trade-offs with limited time and cognitive capacities (Herfeld, 2020a, 2020b; Simon, 1991, 1997; Todd & Gigerenzer, 2007). Philosophical accounts highlight context-dependent pros and cons, alongside resolving uncertainty and conflicts (Dietrich & List, 2013; Shafir et al., 1993). These frameworks pose implementation challenges in empirical research.

In our study, we attempt to take a pluralistic stance and concentrate on factors that draw on rational choice theories but mostly to the reasons humans provide to justify their choices. Our core aim is to evaluate how each of these factors, assuming they are integrated into the agent's decision-making process or their subsequent assessment of the decision, affect their sense of agency in a complex, multi-stage choice task. It's important to note that these factors are not meant to strictly match or be exhaustive of all aspects or theories of rationality or practical reason, nor are they ranked in terms of significance. They were selected for their recognized relevance to people's reasons for choosing or justifying their actions, making them compelling candidates to explore for their potential impact on our sense of agency. In what follows, we therefore use the word "rational" and "reasonable" interchangeably as referring to the ways humans tend to rationalize their choices.

First, we propose that a rational choice involves selecting an option based on its comparatively higher expected value relative to other options, rather than randomly choosing between options of equal value, regardless of the actual outcome (which, in a probabilistic task, can be either positive or negative, with limited control over it). This definition of rationality and rational choice serves as our first operationalisation of the concept and will be referred to as R1 in the subsequent sections of the paper. Research indicates that agents commonly consider differences in value between options in their selection process (Shafir et al., 1993; Ullmann-Margalit & Morgenbesser, 1977). We hypothesize that agents perceive their choice as more rational (in the R1 sense) when selecting from diverse options and opting for the one they deem superior, compared to making a random selection between identical options (H1).

Secondly, in a simplified choice between two risky alternatives offering rewards, a decision is seen as justified insofar as the agent has nothing to regret. This absence of regret refers to two aspects: first, the agent gets a reward (rather than none) and second, the agent cannot think they could have gotten a bigger reward by choosing the other option. These two conditions are satisfied only in cases where the agent chooses the option with the highest expected utility and wins (Second operationalization of rationality and rational choice, R2). In these cases, we expect that people will feel more agency than when they can hover over regrets for losing or not choosing the better option (H2; regarding this, see Discussion and Supplementary Material for additional analyses).

Thirdly, we propose that agents are concerned not only with the options currently available to them but also with further potential alternatives, including possibly superior options that are not accessible to them. The inclusion of this feature deserves more justification, as it may not immediately connect to mainstream theories of rationality, but still is part of everyday human considerations. More specifically, rational agents are expected to evaluate all alternatives and choose the one which predicts the highest utility. In this process of prediction, they not only anticipate the option they should choose but also consider those they will not select. In humans, this phenomenon is studied and reflected in the anticipated regret for unchosen available options (Zeelenberg, 1999). We are here tapping, however, into a different kind of regret over potential but unattainable options, a phenomenon we refer to as 'Possible Missed Opportunities' (PMO) (H3).

Extant evidence suggests that the above-mentioned regret over unchosen available options is not unique to humans but is also observed in non-human primates (Fouragnan et al., 2019) – showing, according to some researchers, that they already exhibit a form of rational agency (Tomasello, 2022). H3 is motivated by the observation that, unlike these primates, humans are sensitive not only to counterfactual outcomes, but also to social or external factors that restrict the range of available options available to them. In other words, their feeling of agency responds not only to their available choice-set but also to the limits of that set. If certain options are known to exist but are practically unavailable, it is arguably rational for individuals to be concerned about missing opportunities that might prove unexpectedly rewarding in the future (third operationalization of rationality and rational choice, R3) (Shin & Ariely, 2004) or restrict the development of their personal preferences and flourishing (Sen, 1988).

In addition to these behavioral expectations, we are also interested in whether the relationship between the types of rationality and rational choice proposed here and the sense of control can be observed in neural signals. To answer this, we used electroencephalography (EEG) and utilized Event-Related Potentials (ERP) in response to different conditions and phases of our decision-making task.

Specifically, our H1 posits that people should process the following scenarios differently: choosing between options with varying expected values versus picking from options with identical expected values. This can be classified as stimulus processing in a decision-making task. Previous research on ERP components in analogous scenarios shows a positive peak occurring around 300–600 ms after stimulus onset, centered around centro-parietal electrode regions (specifically, P300). The amplitude of this component is sensitive to perceived evidence (Twomey et al., 2015) in perceptual decision-making paradigms. In addition, it was shown that the P300 amplitude is also sensitive to risk and ambiguity in value-based decisions (Deng et al., 2023). We expected to see a difference in P300 amplitudes between choosing from different alternatives and picking from identical options, although participants made the rational choice in both cases.

In line with H2, the processing of action outcomes has been shown to elicit a negative-going wave around 200–300 ms after outcome onset, centered around fronto-central electrode sites (San Martín, 2012). This component, known as the Feedback-Related Negativity (FRN), has been shown to increase in magnitude when the outcome of action is negative or unexpected (Nieuwenhuis et al., 2004). Relatedly, we anticipated a higher FRN amplitude when participants made "irrational" choices that yielded a reward (H2). However, to check whether our paradigm successfully captured outcome processing, we also expected to see a higher FRN amplitude in response to negative outcomes compared to positive ones, regardless of the rationality of the action (see Supplementary Material for details).

Finally, we were interested in how potential missed opportunities might affect participants' affective processes, even though feeling regret about these opportunities implies engaging in counterfactual speculation (H3). To this end, we focused on the Late Positive Component (LPC) in EEG signals, a long-lasting positive-going waveform centered around centro-parietal electrodes, observed when a participant perceives an affective and/or arousing stimulus (Hajcak & Foti, 2020). In line with H3, we expected that realization of possible missed opportunities would yield higher LPC amplitudes compared to trials in which participants were presented with all the possible options.

We emphasize that R1, R2, and R3 identify three complementary, rather than mutually exclusive, facets of how humans reason about their choices. If these aspects influence decisions or the way people reflect on their decisions, they are expected to play a role in shaping their sense of agency. Hence, we chose to test our 3 hypotheses (H1, H2, and H3), linked to our 3 definitions of rationality and rational choice, concurrently within a single task. Importantly, we also hypothesized that any systematic differences in people's sense of agency should be reflected in corresponding differences in brain activity. To explore whether differences in the sense of agency relate to the perceived rationality of the decision-making process, and to identify which elements of rationality are most involved, we combined direct methods (self-reports) with indirect methods (brain signal measurements).

## 2. Materials and methods

### 2.1. Participants

After data exclusion (see Supplementary Material for details), the current sample consists of 53 participants for behavioral analysis (*Age: Mean* = 25.72 years, *SD* = 5.25; 30 females), and 46 participants for EEG data analysis (*Age: Mean* = 25.85 years, *SD* = 5.28; 24 females). All participants received a written informed consent form before the study and the experiment received ethical clearance through the School of Advanced Study, University of London ethical approval (SASREC-1819-

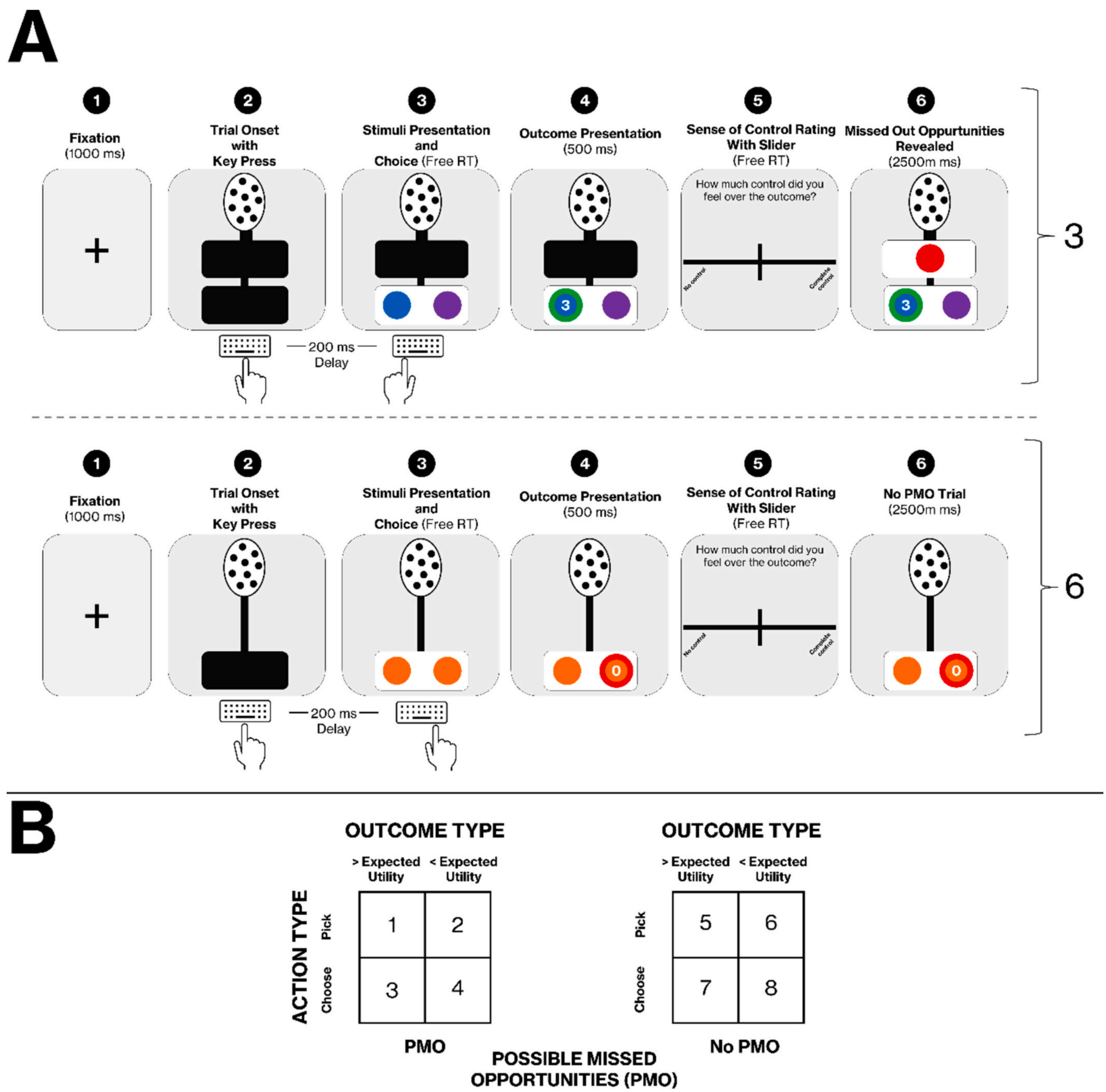


**Fig. 1.** JAR Task and Study Design. Panel A shows 2 example trials from the JAR task in detail. The top row shows an example PMO trial, where the rewarding option was chosen among two different options and there was only 1 missed out alternative. The bottom part of Panel A shows an example of a No PMO trial, where the non-rewarding option was picked among two identical options. Panel B shows all possible trial types of the task. The numbers on the right-hand side of Panel A and within the squares of Panel B represent 8 different trial types, each defined by a combination of manipulated variables. For instance, the trial presented on the top row of Panel A is a choose trial where there was a possibility of missed opportunities and the outcome was higher than expected utility, corresponding to trial type 3.

313R).

### 2.2. Experimental task

A computer-based two-alternative forced choice task that we called the JAR task was programmed in Matlab with Psychtoolbox extensions (Brainard, 1997; Kleiner et al., 2007) and stimuli were presented on a 24-in. LCD monitor. In its overall structure, this task is like a game of bingo lottery combined with a simple value-based choice. The participant's display (Fig. 1) shows, at the top, a circular jar with several black balls bouncing inside it. This jar is connected, via a pipe, to one or two boxes sitting one on top of the other underneath the jar. The participant is told that, in each trial, after they press the spacebar, some balls will fall through the pipe: if there is a single pipe and box, only 2 balls will fall into the box and participants will have those 2 options to select from, with no possibly missed opportunities (No PMO trials); if there is also an upper box and a pipe, 2 balls will always continue their journey to the lower box (as in No PMO trials), but it is possible that none, 1, or 2 additional balls fall into the upper box, creating the potential for missing opportunities (PMO trials). In both cases, when the 2 balls reach the lower box, this box lights up and the participant gets to choose between one of the two balls. Then, the chosen ball's value and the content of the upper box (i.e. the color of the lingering ball) are revealed, and the game proceeds to the next trial. The purpose of the game is to find out – through trial and error – which color has the higher value and accumulate as much monetary reward as possible.

Each trial of the task starts with a fixation cross displayed for 1000 ms in the middle of the screen. It is followed by the initial presentation of the jar with whirling black balls inside of it. As mentioned, if a given trial is a PMO trial, then the jar is connected to 2 black boxes, if it is a No PMO trial then the jar is connected to one black box (Box of options display). In both trial types, after participants press the button, the selection space becomes transparent, revealing the 2 different alternatives for that specific trial. Once participants select one of the balls by pressing a key on the keyboard ("F" for the left-side option with their left index finger and "J" for the right-side option with their right index finger; all participants were right-handed and used the same fingers throughout the experiment), the outcome of their choice is displayed. If they choose the rewarding ball, the surrounding area of the chosen ball turns green, and the value associated with the ball is displayed inside of it. If their choice is non-rewarding, the outside of the selected ball turns red, with the number "0" displayed inside. This end-of-trial feedback was implemented for participants to learn value-color contingencies, when they chose the rewarding option. Importantly, regardless of whether participants choose the rewarding option, they do not learn whether the non-chosen option would have yielded a positive or negative outcome.

Subsequently, the display changed, and participants were asked to rate how much control they felt over the outcome with a slider. The scale ranged from "no control" to "complete control" at its extremes, with no intermediate numerical or verbal values.

To make their rating, participants used two keyboard keys ("F" to move left and "J" to move right), with which they could move a red cursor on the slider. In each trial, the cursor was initially positioned in the middle of the slider and each key press shifted it by 10 pixels, with the possibility of holding it down to move it smoothly along the scale. The rating was confirmed after pressing the spacebar. Finally, in the case of a PMO trial, the content of the upper black box (PMO Box) is revealed, showing the possibly "missed" opportunities. Importantly, as mentioned, not all PMO trials included possibly missed opportunities. Some PMO trials included 1 or 2 missed opportunities, while "PMO Empty" trials revealed that there were none missed opportunities in the black box. In case of a No PMO trial, participants were simply shown the action outcome again. Panel A of Fig. 1 shows two different trial types in detail. Panel B of the same figure shows all possible trial types, as combinations of the 3 main factors of interest (Action type: choosing vs. picking randomly; Outcome Type: Higher or lower than expected utility; PMO condition: PMO or No PMO trials.)

The balls were of four different colors (orange, light blue, purple, yellow), each associated with a fixed numerical value (1, 2, 3, 4 points). However, due to the probabilistic nature of the task, the outcome of a given choice could be positive or negative, irrespective of the potential value of the selected ball. Out of 240 total trials, 120 yielded positive results and 120 negative results: the probability of receiving a positive outcome for each individual choice was 50 %. Therefore, participants received 1 to 4 points in half of the trials and 0 points in the other half.

Given this probabilistic nature, each option was associated with a distinct expected utility, calculated as the weighted average of the potential positive outcomes for that option (again, 1, 2, 3, or 4 points, depending on the color), with the weight determined by a consistent probability of winning, set at 0.5. For example, in a choice between a yellow and an orange ball, the expected utility is higher for the yellow ball (50 % chance of winning 4 points) compared to the orange ball (50 % chance of winning 1 point), making the yellow ball the more rational choice, regardless of the actual outcome, which could still be negative. Since the probability of winning is always 0.5, the actual outcome exceeded the expected utility whenever participants won in a given trial (Outcome type: Higher than expected utility); conversely, when they lost, the outcome fell below the expected utility (Outcome type: Lower than expected utility).

Combinations of colored balls were equally balanced across the experiment: since ten combinations of colors/points (1–1, 1–2, 1–3, 1–4, 2–2, 2–3, 2–4, 3–3, 3–4, 4–4) were possible (six with balls of different colors and four with balls of the same color), each combination was repeated twelve times throughout the experiment. The placement of the colored balls in the space of choice (left or right side) was also alternated. All combinations of all different levels of independent variables were presented equally to the participants in a fully randomized order (Fig. 1, Panel B). The jar task was administered over four blocks of 60 trials each (240 trials in total), after completing 10 practice trials. Participants received performance feedback after every 15 trials. The entire experimental session, including instruction and practice phases, lasted around 45 min.

In the instruction phase, participants were not informed of the exact probability distributions (50 % chance of winning) but were told that each individual option they selected could yield a positive or a negative result on a trial-by-trial basis. Similarly, they were not initially informed of the specific number of points associated with each color (e.g., orange = 1 point) but were told that each color was consistently associated with a fixed numerical value throughout the entire experiment. Participants were further informed that every possible combination of colored balls could come into the selection space, including two identically colored balls. They were instructed that at the end of each trial, they would rate how much control they felt over the outcome by using a slider. Importantly, we avoided influencing participants' responses by not providing any guidance on what to base their judgments, such as whether they won or lost or whether they experienced a PMO or a no PMO trial.

Participants were also instructed before the task that they could gain bonus monetary rewards (up to €1.50) depending on their performance. However, due to the predetermined structure of the task, they all received the same bonus amount at the end of the experiment.

### 2.3. EEG recording and preprocessing

Continuous EEG was recorded by using a 64-channels (*EasyCap, actiCap, Brain Products GmbH, Gilching, Germany*) BrainVision amplifier with a sampling frequency of 1 kHz. Ag-AgCl electrodes were placed according to the international 10–20 system. EEG signals were recorded with a 0.1 Hz high pass filter. Horizontal and vertical eye movements were recorded simultaneously by an electrode placed below the left eye. All electrodes' impedance levels were kept below 25 kΩ.

EEG preprocessing was done by EEGLAB version 2022.0 (Delorme & Makeig, 2004) and custom MATLAB scripts. First, continuous data were down-sampled at 250 Hz and a band-pass filter between 45 and 55 Hz was applied to remove line noise. Continuous data were then cropped into epochs, relative to the onset of events of interest. Each participant had 600 epochs in total (240 were time-locked to the onset of the balls, 240 were time-locked to the onset of the outcome and 240 were time-locked to the PMO condition being revealed), with a length of 5 s each (1-s pre-event period and 4 s post-event period). Epochs for testing H1 have the onset of the stimulus presentation at time = 0. For H2, we used the onset of the outcome presentation. Finally, epochs for testing H3 have the onset of the revelation of the black box at time = 0. Following epoching, noisy channels were interpolated via spline interpolation (mean number of interpolated channels, 1.20 (2 %), $SD = 1.10$). Then, epochs containing artifacts were visually inspected and rejected from further analysis (mean number of rejected epochs, 77.84 (2 %), $SD = 63$). Finally, ICA was used to remove heartbeat and eye movement-related activity. Pre-processed data were averaged across channels and baseline corrected (200 ms pre-trigger) relative to the event onset, per each type of ERP component separately. Stimulus onset (H1) was defined as the moment when the two alternative options were presented, i.e., when the (lower) box with the two balls was revealed. Outcome onset (H2) was defined as the moment when the outcome was presented, i.e., when the number of points appeared in the chosen ball. Finally, the onset of possible missed opportunities (H3) was defined as the moment when the content of the black box was revealed (see Fig. 1).

### 2.4. Statistical analysis

All statistical tests were done with RStudio version 2023.06.0 (RStudio Team, 2020) via lme4 package (Bates et al., 2015) by building linear mixed-effects models. In all models, subjects were included as random slopes and factors were included as fixed effects. For behavioral data, a full model including all 3 factors and their interactions was run (see Supplementary Material).

Hypothesis testing on EEG data was done by 3 models including 3 different ERP components. To test H1 (see Introduction), the mean amplitude of the P300 component was used. The mean voltage from 3 channels (CZ, CPz, and PZ) during 400–600 ms post-stimulus onset was calculated per trial on baseline-corrected epochs (Polich, 2007). To test H2, Feedback-Related Negativity (FRN) was used as an index of outcome processing (Cohen et al., 2007; Hauser et al., 2014). The mean FRN amplitude of the FCz electrode over 250–350 ms post-outcome onset per each baseline-corrected epoch was calculated. Finally, H3 was tested using the Late-Positive Component (LPC) as an index of affective processing and the mean LPC amplitude was calculated over CPz during 500–1000 ms post-event onset (i.e., onset of the revealing black box content) time window (Liu et al., 2012). Akin to behavioral models, we tested the fixed effects of Action Type (picking vs. choosing), Positive Outcome by Rationality of the Choice (positive outcomes after rational choices vs. positive outcomes after irrational choices), and Possible Missed Opportunity (absent possibility vs. present possibility). In all models, participants were included as random effects.

Finally, to relate reports and brain measures, we focused on whether EEG metrics of interest predict sense of control ratings. To do this, we ran a linear mixed-effects regression model including the mean amplitudes of FRN and P300 as fixed factors to predict SoC ratings while adding participants as random effects. Due to the temporal order of our task design (see Fig. 1, time course of events during a trial), we did not include the LPC amplitude as a predictor of sense of control ratings in this model.

## 3. Results

### 3.1. Behavioral results

#### 3.1.1. H1 - SoC rating and action type

Our first model revealed a significant effect of Action Type on the SoC ratings (Fig. 2). Participants reported higher levels of SoC when they were able to *choose* between different alternatives (different-color balls), compared to randomly *picking* one of the identical options (same-color balls) ($\beta = 0.09$, [0.08–0.10], $SE = 0.01$, $p < 0.001$).

#### 3.1.2. H2 - SoC rating and rationality of the choice

To test the effect of rational choices leading to positive outcomes (for rational choices) on the SoC ratings, we refined our dataset by excluding picking trials (i.e., picking between identical options) and trials with negative outcomes (i.e., outcome is lower than expected utility). This process left us with a subset that includes only positive outcome trials (i.e., outcome is higher than expected utility) resulting from rational choices. This approach aligns with H2, as we anticipated that participants would feel more agentive (reflected in higher SoC ratings) when they choose the rational option (i.e., maximizing expected utility), given that they have varied values to choose from, and when the outcome is positive (i.e., they win).

Our linear mixed-effects model showed that receiving a positive outcome yielded significantly higher SoC reports if preceded by selecting the option with higher expected utility (rational action) compared to selecting the lower expected utility option (irrational action) ($\beta = 0.09$, [0.08–0.10], $SE = 0.01$, $p < 0.001$). (Fig. 2)

Finally, to test the effect of choice rationality on sense of control, independent of outcome type and reward magnitude, we conducted a follow-up analysis. Similar to the main analysis reported above, this follow-up analysis focused only on choose trials with a positive outcome. However, we limited the dataset to trials in which participants gained either 2 or 3 points. This allowed us to directly compare rational and irrational choices regarding their effects on the sense of control ratings, while keeping reward magnitude constant. Our regression model showed no significant effect of choice rationality on sense of control ratings for trials where the reward value was 2 ($\beta = 0.002$, [0.01–0.02], SE = 0.01, $p = 0.79$). In contrast, for trials with a reward value of 3, there was a significant effect of choice rationality on sense of control ratings, ($\beta = 0.03$, [0.002–0.05], SE = 0.01, $p = 0.03$).

#### 3.1.3. H3 SoC rating and possible missed opportunities

Finally, a significant effect of Possible Missed Opportunities on SoC ratings was observed. When faced with the possibility of missed opportunities (i.e., black box trials), participants reported lower levels of SoC compared to trials where the possibility of missed opportunities was absent (i.e., no black box trials). ($\beta = -0.01$, [−0.02 – -0.01], $SE = 0.01$, $p = 0.002$). (Fig. 2)

### 3.2. EEG results

#### 3.2.1. ERP predictors of sense of control ratings

Firstly, we examined the relationship between our ERP components and sense of control ratings. Our regression model showed that both mean FRN amplitude ($\beta = 0.16$, [0.14–0.18], $SE = 0.01$, $p < 0.001$) and mean P300 amplitude ($\beta = -0.04$, [−0.6 – -0.2], $SE = 0.01$, $p < 0.001$) significantly predict proceeding sense of control ratings (Table S13).

#### 3.2.2. Action type - P300b

Our linear mixed-effects regression model revealed a significant effect of Action Type on the P300 component, such that the mean P300 amplitude was significantly higher for picking than choosing ($\beta = -1.09$, [−1.40 – -0.79], $SE = 0.16$, $p < 0.001$). (Fig. 3)

#### 3.2.3. Positive Outcome & Rationality of the choice - feedback-related negativity (FRN)

We focused on the Feedback-Related Negativity ERP component to test our second hypothesis with EEG data, specifically to determine if this EEG component would reflect prediction error. Importantly, when we applied a similar filtering process for trials as we did for behavioral data, we ended up with less than 30 trials for some subjects, which is

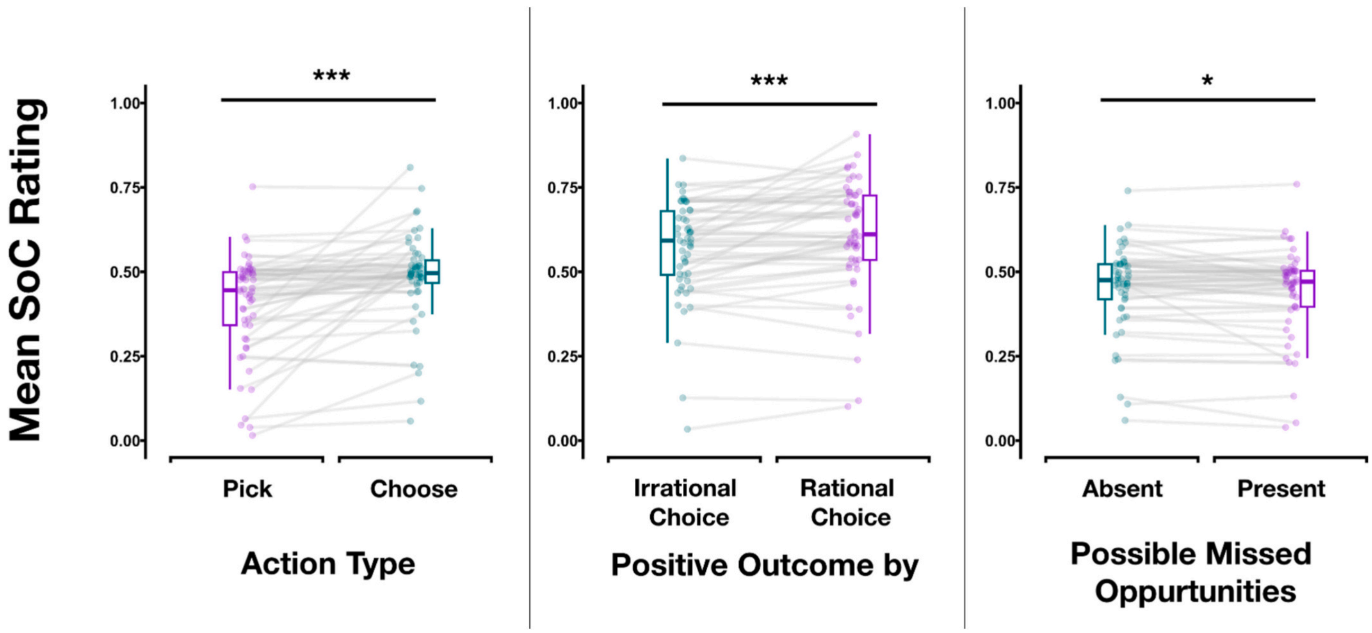


**Fig. 2.** Results of linear mixed-effect models for each predictor. From left to right, plots show the mean SoC ratings per subject as functions of Action Type, Positive Outcome by Rationality of the Choice, and Possible Missed Opportunities, respectively. Single dots indicate the mean SoC ratings of each participant per condition. Gray lines connect the mean values of a given participant's data points. Boxes show 50 % of the distributions, and horizontal lines in the boxes indicate the median of the distributions. Vertical lines show interquartile ranges. Sense of control rating values on the y-axis of each plot are normalized values (between 0 and 1) of the original rating scale, which was between 0 and 100. * *p < 0.05,* *** *p < 0.001.*

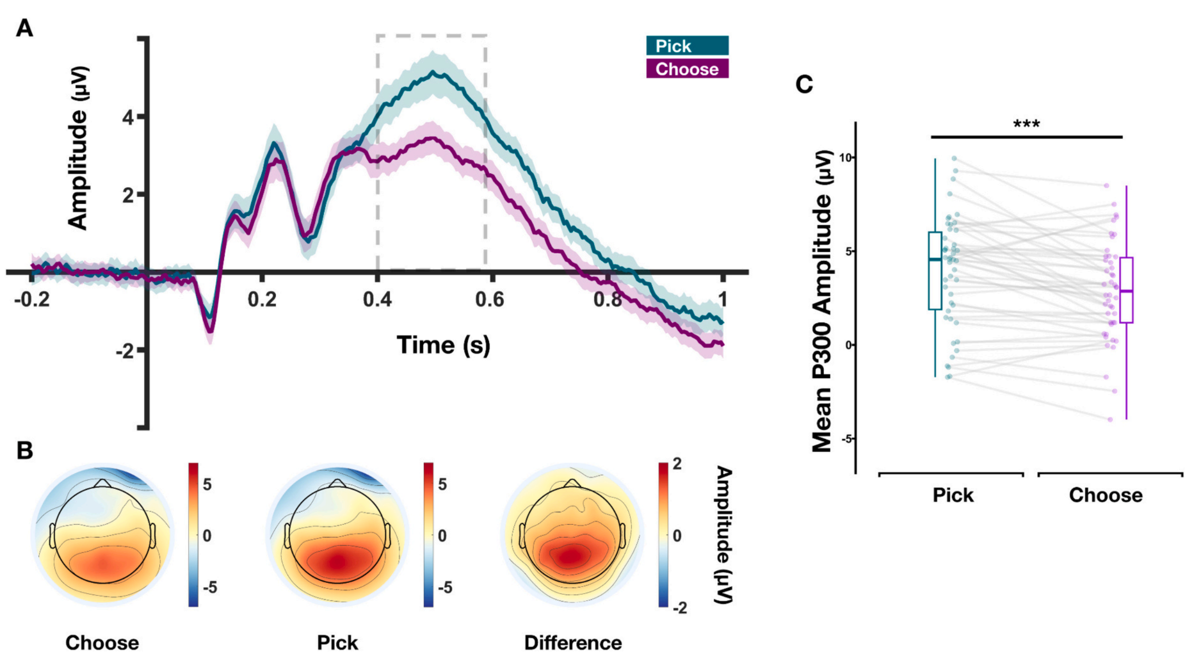


**Fig. 3.** Effect of action type on EEG signal. Panel A: Grand-averaged ERPs, time-locked to the onset of either different (Choose) or identical (Pick) alternatives on the computer screen. The gray dashed line indicates the time window for P300 amplitude calculation. Shaded areas surrounding the traces indicate ±1 SE of the EEG signal (across participants). Panel B: The topographic plots show the amplitude difference between conditions during the time window of interest. Panel C: Single dots show the mean P300 amplitude for each participant per condition. Boxes show 50 % of the distributions, and horizontal lines in the boxes indicate the median of the distributions. Vertical lines represent interquartile ranges. *** *p < 0.001.*

below the acceptable limit for ERP analysis. However, we continued our analysis nonetheless, since our statistical test operates in a trial-wise fashion. Our linear mixed-effects regression model revealed no significant effect of Positive Outcome by Rationality of Choice, meaning there was no difference in mean FRN amplitude between obtaining a positive outcome from choosing the rational option versus the irrational option ($\beta = -0.39$, [−1.12–0.34], $SE = 0.37$, $p = 0.29$). (Fig. 4)

### 3.2.4. *Possibly missed opportunities - late-positive component (LPC)*

To assess the effect of possibly missed opportunities (PMO) on the LPC amplitude, we ran a linear mixed-effects regression model. The model includes PMO condition as fixed effect with 3 levels: trials

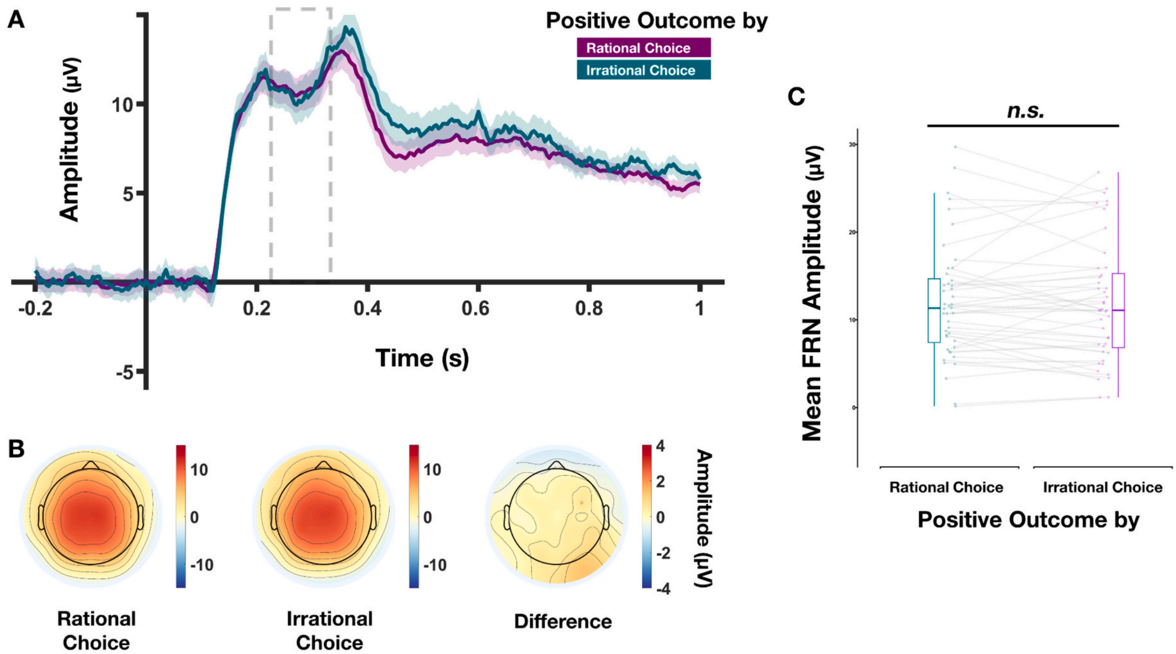


**Fig. 4.** Effect of rationality of the choice that results in a positive outcome on EEG signal. Panel A: Grand-averaged ERP plots, time-locked to the onset of the outcome phase. The rectangular area enclosed by a gray dashed line indicates the time window for FRN amplitude calculation. Shaded areas surrounding the traces indicate ±1 SE of the EEG signal (across participants). Panel B: The topographic plots show the amplitude difference between conditions during the time window of interest. Panel C: Single dots show the mean P300 amplitude for each participant per condition. Boxes show 50 % of the distributions, and horizontal lines in the boxes indicate the median of the distributions. Vertical lines represent interquartile ranges. *** *p < 0.001*.

without the black box (No PMO), trials with a black box which is revealed to be empty (PMO Empty - PMO without possibly missed opportunities), and trials with a black box which is revealed to contain one or two balls (PMO Present).

Results showed that mean LPC amplitude was significantly higher when PMO is present, compared to no PMO trials ($\beta = -0.94$, [−1.33–0.54], $SE = 0.20$, $p < 0.001$), and trials where PMO is absent ($\beta = -1.21$, [−1.75–0.68], $SE = 0.27$, $p < 0.001$). Pairwise comparisons also showed that LPC amplitude did not differ between No PMO and PMO Empty trials. (Fig. 5)

## 4. Discussion

Previous studies on human agency commonly highlight the effect of

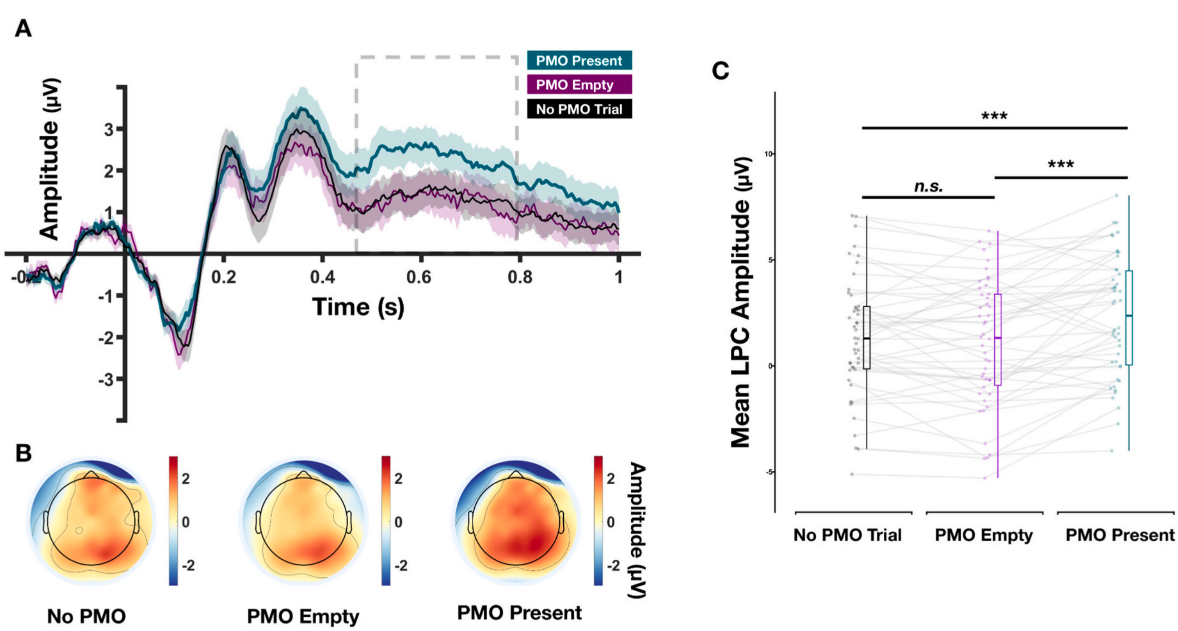


**Fig. 5.** Effect of Possibly Missed Opportunities on EEG signal. Panel A: Grand-averaged ERP plots, time-locked to the onset of the content of the black box revelation. The rectangular area enclosed by a gray dashed line indicates the time window used for mean LPC amplitude calculation. Shades surrounding the traces indicate ±1 SE of the EEG signal (across participants). Panel B: The topographic plots show the amplitude difference between conditions during the time window of interest. Panel C: Single dots show the mean LPC amplitude for each participant per condition. Boxes show 50 % of the distributions, horizontal lines in the boxes indicate the median of the distributions. Vertical lines represent interquartile ranges* *p < 0.05, *** p < 0.001.*

outcomes on our self-reported sense of agency. The infamous phenomenon known as "outcome bias" shows that we, humans, report higher levels of sense of control when our actions yield positive outcomes compared to neutral or negative ones. However, in this study, we examined whether making rational decisions – according to the multifaceted understanding of rationality discussed in the Introduction – also influences our reported sense of agency. We hypothesized that our participants would be sensitive to the type of action they performed, beyond the effect of the outcome, when they report agency (in accordance with R1).

Previous studies have shown the effect of "action type" on SoA reports, such that when participants are forced to select a certain option among others, they report less agency compared to choosing "freely" (Barlas et al., 2017; Giersiepen et al., 2023; Murayama et al., 2015). In our study, we introduced a novel "choice freedom" dimension such that participants were not explicitly instructed to make a "forced" choice: they simply had to "pick" between two identical options rather than "choosing" among options with different value associations. As we expected, they reported higher levels of SoC during those "choose" trials compared to "pick" trials.

This result can be interpreted as follows: regardless of the outcome, when humans make decisions that cannot be rationally justified (*rational* in the sense of R1), they express less sense of agency, something that we believe is a novel finding, which might highlight an aspect of the sense of agency that is specific to humans. In other words, compared to other mammals, humans might experience and report a sense of agency that goes beyond goal-directed action-outcome contingencies but also consider having reasons to make decisions. Importantly, future studies should focus on the distinction between forced choice, picking, and free choice to elucidate whether humans show sensitivity for each type of choice behavior.

Secondly, we expected that, in reporting the sense of control, our sample would show sensitivity not just to the outcomes of their actions, but also to whether their choice was rational or not (*rational* in the sense of R2*)*. Our experimental design and data processing allowed us to test whether participants would report higher levels of sense of control when their decision was "rational", based on value associations that they learned during the task, compared to "irrational" decisions. The concept of expected utility, rooted in normative models like those of Von Neumann & Morgenstern (1947), is quantified as the weighted average of all potential outcomes of each given option, with the weights being their respective probabilities.

In our game of chance, where the choice is between two balls, one promising a potential win of 4 points and the other 2 points, each with a 50 % chance of winning, the rational choice can be deduced by calculating the expected utility of each option. For the ball offering a 4-point win, with a winning probability of 0.5, its Expected Utility = Probability × Points = 0.5 × 4 = 2. Similarly, the ball offering a 2-point win also has a 0.5 chance of winning, yielding an expected utility of 0.5 × 2 = 1. Therefore, since the expected utility for the 4-point ball is 2, and for the 2-point ball is 1, the rational decision, based on maximizing the expected utility, would be to opt for the ball offering 4 points. Other views, grouped as ecological, bounded, or adaptive theories of rationality, challenge that maximization is the rational theory under all circumstances. However, in this simplified context, these theories would also accept that choosing the expected better option is rational, and reason-based perspectives would agree that there are more reasons for such a choice. What matters is that winning the higher amount of 4 points not only simply accrues the overall utility (4 is the best possible outcome) but also goes beyond the expected utility – it represents a positive prediction error. Even in a game of chance, there is a tendency for individuals to ascribe their fortunate outcomes to their own actions. Gerstenberg et al. (2018) demonstrated that individuals tend to feel more responsible when an action leads to unforeseen, more favorable outcomes and is perceived as indicative of potential future success. In line with this perspective, our participants reported a higher sense of control when they "won" after making rational (rather than irrational) decisions.

That being said, regarding rationality of the choice on sense of control, it is also important to highlight here that our additional analysis on this topic yielded some interesting results. To control for the influence of reward magnitude on sense of control ratings, we limited our analysis to the trials where the reward magnitude was equal and compared rational and irrational choices in terms of the reported sense of control levels. Two separate analyses conducted on two subsets of our data produced divergent results. While we found no effect of choice rationality on sense of control in trials where the reward was 2 points, a significant effect emerged for trials with a 3-point reward.

We believe that these seemingly conflicting results may be explained by the mean expected value for each trial. The option set of our experiment included colored balls with values of 1, 2, 3, and 4; while with 0 points awarded in non-rewarding trials. Hence, the average expected reward across trials was exactly 2 points (but see Supplementary Material for an alternative calculation and results). Hence, it might be that our sample was sensitive to rationality of their choices only when the reward in a given trial exceeds this average, thus creating an opportunity for a "positive surprise". To test this possibility, we conducted an ad-hoc analysis (see Supplementary Material) to assess whether participants were indeed sensitive to the mean expected value. Our results provide supporting evidence for this view, showing that participants' sense of control was also modulated by reward magnitude in relation to the mean expected value. Based on these findings, in relation to H2 we cautiously conclude that while choice rationality plays a role in shaping sense of control, its effect is not entirely independent of the magnitude and expectancy of rewards. Given that these last two analyses were conducted ad-hoc, we encourage future researchers to consider these factors when designing their studies.

Finally, we were also interested in the effect of available options on participants' sense of control over the outcomes of their actions. Importantly, this uncertainty was not cleared away before participants rated their sense of control for the given trial. Our result showed that people reported less sense of control when there was a possibility of missed opportunities. In other words, humans care not only about the type of their actions and their outcomes, but also about whether they were presented with all possible alternatives. Crucially, this effect cannot be attributable to the outcomes since our comprehensive statistical model (see Supplementary Material) included all factors, yet the effect remained significant.

To further clarify, the PMO and no PMO conditions were identical in terms of the number of options available to participants (always 2 in both conditions). The only visual difference between the trials was the presence of an intermediate black box in the PMO condition, located between the jar and lower box, with its content revealed only after participants made their ratings. During the instruction phase, participants were instructed that in the PMO condition up to four balls were first extracted from the jar and placed in the upper box, with two balls then moved to the lower box. While the black box could have caused occasional distraction, our findings show that participants consistently reported feeling less control in the PMO condition. If the black box caused distraction, leading to lower sense of control ratings, one might expect to see this effect to be diminished or lessened across time. To check this possibility, we ran an additional analysis (see Supplementary Material) in which we only included the second half of the trials. It was shown that the originally observed PMO effect was still significant. This supports the hypothesis that the potential presence of hidden and inaccessible options is sufficient to negatively impact the sense of control.

Following our behavioral analysis, we focused on the neural processing of sense of control and how it relates to our factors of interest. First, we showed that known EEG markers of decision-making (i.e., P300) and outcome processing (i.e., FRN and LPC) were observed in the current dataset. Our regression model also showed that both the P300 and FRN are significant predictors of SoC ratings in our task. Importantly, the effect of outcome processing on the SoC ratings was much higher than the P300 effect, in line with the previous studies involving neuroimaging methods, sense of control, and agency (El Zein et al., 2022; Sidarus et al., 2017). Thus, we were able to replicate the existing findings in the literature before focusing on our research questions covering SoC, rationality, and the neural markers of their relationship.

First, we examined the centro-parietal P300 as a marker of stimulus processing during the evaluation phase of the presented alternatives. Notably, trials in which participants had to pick between identical options resulted in higher P300 amplitude compared to trials where they chose between different alternatives. This finding suggests that the evaluation of alternatives may engage distinct cognitive processes depending on the nature of the choice.

Traditionally, the P300 amplitude has been associated with levels of cognitive processing (Polich, 2007). However, another hypothesis regarding the nature of the P300 suggests that it can be considered as a "build-to-threshold" signal that ramps up until a decision threshold is reached via accumulating evidence (Twomey et al., 2015). This built-to-threshold signal is shown to be present in both perceptual and value-based decision-making tasks (Polanía et al., 2014). Our results can be explained better with the former cognitive processing hypothesis, as we have observed a higher P300 amplitude during trials with "less evidence" for reaching a decision threshold.

Specifically, when participants were presented with two identical options and given the chance level outcome structure of our design, it was very difficult to reach a decision based on the available evidence. In contrast, in "choose" trials, participants were able to reach a decision by following color-value associations. Hence, "choose" trials would allow accumulating more evidence, leading to a higher P300 amplitude. However, we observed the opposite. One explanation for this result could be that when participants encountered "pick" trials, the decision difficulty was maximum due to the lowest possible value difference. Hence, more cognitive processing due to this difficulty could result in a higher P300 amplitude.

Importantly, in their review, Ghani et al. (2020) conclude that an increased P300 amplitude is associated with decreased cognitive load. Although this may appear contradictory to our results, given that comparing "picking" and "choosing" behavior is a novel aspect of our study, we believe further investigation is required on the neural dynamics of this distinction.

We used the FRN as a metric for outcome processing, to test whether receiving a reward after making a rational decision (choosing the option with higher expected utility) would differ from receiving a reward after making an irrational decision (choosing the option with lesser expected utility), as we proposed with R2.

FRN is suggested to encode prediction errors and to be sensitive to the magnitude of the difference between expectations and outcomes (Sambrook & Goslin, 2015). Importantly, it has also been shown to be an "unsigned" prediction error, suggesting that both positive and negative prediction errors would elicit this ERP component (Talmi et al., 2013). Relatedly, one possibility is that when participants made an irrational choice in a trial and received a higher-than-expected utility outcome (i.e., positive prediction error), this would elicit a bigger FRN compared to making the rational choice and receiving a reward. However, our results showed no difference in the FRN amplitude between the conditions.

There may be several explanations for this result. One possibility is that the limited number of trials may not produce sufficient data to produce reliable ERP traces for irrational choices (see Supplementary Material). Our participants mostly chose the rational options, which left us with few "irrational" trials. This might affect the waveform shape of ERPs and result in unreliable signals (Cohen, 2014). Thus, we hesitate to conclude that the FRN was not sensitive to positive prediction errors in our design. We also emphasize the need for future studies to account for this finding and ensure a sufficient number of irrational trials.

Alternatively, while participants may not know the exact probability of winning (which is consistently 50 %), contrary to H2, there might be no inherent motive to expect them to be more surprised by a win following an irrational choice compared to a rational one. In the end, the rational choice provides a higher potential reward, but it does not increase the absolute likelihood of winning. Consequently, after making a choice, participants could feel equally surprised by a win, regardless of the rationality of their decision. In this case, since both rewarded rational and rewarded irrational trials would be equally surprising for participants, one might not see a difference in the FRN between the two trial types but only a difference in the FRN between rewarded and non-rewarded trials. In this context, we conducted an additional analysis (see Supplementary Material) to ensure that the outcome valence effect of the FRN was present. Results reliably showed that outcomes that are lower than expected utility produced bigger FRN compared to higher-than-expected utility outcomes. Thus, another potential explanation for the observed FRN effects could be that the FRN is mostly sensitive to the outcome of actions, with negative outcomes yielding higher FRN than positive outcomes (See Supplementary Material).

Finally, regarding the influence of PMO context on neural signals, our analysis, using the late positive complex / potential (LPC) as a proxy for affective processing, demonstrated that trials without any PMO context and trials with PMO context but without missed alternatives resulted in similar EEG signals. However, when participants realized that there had been hidden possible alternatives during the decision phase, the LPC amplitude increased. The LPC has been associated with the affective processing of stimuli, especially in the visual modality. Larger LPC amplitudes are typically observed when the stimulus is pleasant or unpleasant compared to neutral images (Schupp et al., 2000). We interpret our LPC finding similarly, such that when people realized there had been possible alternatives (even if unattainable), they may have experienced a form of "counterfactual regret". Hence, we conclude that our results show evidence in favor of humans' sensitivity to non-presented options, both at the behavioral and neural level.

### 4.1. *Limitations and future research*

We believe there are certain limitations of our study that need to be addressed. First, our design did not include all potential determinants of human rationality to be tested within the context of the sense of agency. Hence, we believe future studies focusing on different aspects of rational decision-making would complement the present findings. Similarly, our explicit measure of the sense of agency was a post-decision and post-outcome evaluation of the decision-making process. Hence, our behavioral results can only be interpreted as post-hoc evaluations of individuals' sense of agency, which limits the scope of our conclusions. Relatedly, it is crucial to note that the design of our experiment did not include any behavioral reports after the missed opportunities were presented to the participants. Thus, the conclusions we draw from the LPC analysis here are speculative rather than showing direct evidence for affective processing. Further, we observed high levels of inter-individual variability in our results, especially for what concerns H3. Thus, we believe that future research should focus on personal factors that would explain this variability. Finally, since we employed a computer-based decision-making task, the external validity of our results is limited regarding their applicability to other decision-making processes.

### 4.2. *Conclusion*

In our study, we examined how the reasons behind our choices influence our sense of agency using both explicit (self-reported) and implicit (brain signals) measures. We found that choices perceived as more rational, involving diverse options, and yielding higher expected utility correlate with a stronger sense of agency, as evidenced by both self-reports and patterns in brain activity.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of the finalized version of this work, the author(s) used ChatGPT and Grammarly in order to copy edit parts of the text (checking for grammar, spelling, and improving readability). After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

## Funding

S.B. has received funding from the European Union's Framework Program for Research and Innovation Horizon 2020 (2014–2020) under the Marie Skłodowska-Curie Grant Agreement No. 754388 (LMUResearchFellows) and from LMUexcellent, funded by the Federal Ministry of Education and Research (BMBF) and the Free State of Bavaria under the Excellence Strategy of the German Federal Government and the Länder. S.B. was further supported by the PRIN project "Distrust in Science Reframed: Understanding and Countering Anti-scientific Behavior" (CUP F53D23010710001 – financed by UE – NextGenerationEU PNRR M4 - C2 - I1.1). L.B. was supported by a grant from the French National Research Agency (ANR-23-AERC-0016). M.Y. was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (819040 – acronym: rid-O). O.D. was supported by the Volkswagen Stiftung Momentum Grant (Co-sense) and NOMIS Foundation (DISE-Project)

## CRediT authorship contribution statement

**Mustafa Yavuz:** Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Sofia Bonicalzi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Laura Schmitz:** Writing – review & editing, Writing – original draft, Conceptualization. **Lucas Battich:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Data curation. **Jamal Esmaily:** Writing – review & editing, Methodology, Formal analysis. **Ophelia Deroy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

Authors declare no conflict of interest.

## Acknowledgements

The authors would like to thank Dr. Bahador Bahrami for his valuable comments and suggestions in revising the manuscript; and Sarah Foss, Joshua Gibbs-Dean, and Uma Naware for their help in the data collection process.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2025.106062.

## Data availability

Preprocessed EEG data, raw behavioral data, and all coding scripts underlying all the analysis and plotting of this article can be openly accessed by the following link: https://doi.org/10.5281/zenodo.13832820

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