The role of intentionality, predictability and their interactions on the markers of voluntary actions. Self-reports rely on what we choose, temporal binding on what we predict, and the readiness-potential on what we act for.

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Introduction

Voluntary actions are characterized by two core features: their self-generated character (i.e., intentionality), and their goal-directedness (Brass et al., 2013; Haggard, 2019; Roskies, 2010). It has been suggested that agents must at least control what to do, or when to do it, or whether to do it (Brass & Haggard, 2008). In order to have a clear goal representation, one must act on a predictable environment (Dolan & Dayan, 2013; Friston, 2009). It would indeed be difficult to engage in goal-directed behaviour if our actions produced unpredictable outcomes. Thus far, the literature has focused on what makes an action self-generated (Dominik et al., 2024; Passingham et al., 2010; Schüür & Haggard, 2011) or on how predictability changes our subjective experience of authorship (Haggard, 2017; J. W. Moore, 2016; Wen & Imamizu, 2022). However, little is known about the joint effects of intentionality and predictability on volition. This study therefore aims to better understand how the different measurements of volition are impacted by different levels of intentionality and of predictability, as well as by their interactions.

Voluntary actions result from intentions and produce consequences. The sequence of events that links intentions with actions and their consequences is associated with a specific phenomenal experience referred to as the "Sense of Agency" (SoA; Frith, 2013; Haggard, 2017; Moore, 2016; Pacherie, 2008; Wen & Imamizu, 2022)—the feeling of being active in a world where our actions produce consequences. The Bayesian cue integration framework (J. W. Moore & Fletcher, 2012; Wen & Imamizu, 2022) proposes that SoA results from the integration of both prospective processes (i.e., intentional, pre-movement) and retrospective processes (i.e., perceived causality, post-movement). The relative weight of these cues depends on their reliability and availability in each situation. This theory provides a flexible explanation of SoA and accounts for its disturbances in conditions such as schizophrenia (for other models of SoA, see : C. D. Frith et al., 2000; Synofzik et al., 2008).

Given that the SoA is phenomenally thin —it is often a subtle, taken-for-granted experience— researchers have developed different methods to measure it. Explicit measures typically involve self-report questionnaires that ask individuals to reflect on their SoA over their actions. In the literature, we have found one study (Saad et al., 2024) that investigated both the contribution of the prospective (i.e., intention-action) and of the retrospective (i.e., outcome-effect) components on reported SoA. In that study, the effect of control was manipulated over both the action and the outcome and measured through the reported SoA. Participants had to drag (with a computer mouse) the image of a desired food item to a grocery cart represented on a computer screen. In the unpredictable action condition, the dragging did not always (?) lead to the item being drop into the grocery cart and participants then had to carry out their action again. In the unpredictable outcome condition, the item being dragged was not always the one that was dropped in the grocery cart. The authors observed that the reported SoA was lower both in the condition with a decreased control over the action, as well as in the condition with a decreased control over the outcome. The authors also observed that the reported SoA was more reduced in the unpredictable outcome condition compared to the unpredictable action condition. This suggests that both the control of the action and of the outcome contribute to the SoA, but that the latter is more important. However, in that study, the unpredictable action condition can be seen as an intermediary outcome (i.e., moving the item to the cart). This would suggest that it is not (solely) the SoA related to the intention of acting that is disturbed, but (also) the SoA related to this intermediary outcome. Moreover, the study relied only on explicit measures, which are vulnerable to cognitive biases, such as the tendency to overestimate one's agency for positive outcomes (Bandura, 1982; Tsakiris & Haggard, 2005). A need of clarification of the contribution of both the intentionality and predictability of the outcome on the SoA remains needed.

Implicit measures aim to capture SoA without relying on report. One of the most widely used implicit measures is temporal binding, a phenomenon in which the perceived time interval between a voluntary action and its outcome is experienced as being shorter compared to a non-voluntary action and its outcome (Haggard et al., 2002). For example, individuals either voluntarily press a button, or a transcranial magnetic stimulation (TMS) pulse over the motor cortex makes their finger press the button. Both actions lead to the occurrence of a tone, and participants are required to estimate the time at which the action and the tone occurred. Results have shown that participants perceive the action to occur slightly later, and the tone to occur slightly earlier when they had pressed the button voluntarily, compared to when the action was the result of a TMS pulse. This forward shift of the time estimation of the action, and the backward shift of the outcome results in a compressed perception of the temporal interval between the action and its effect. This compression of time between the action and the outcome has been referred to as ‘Intentional Binding’ or ‘Temporal Binding’ (TB). The TB effect has been widely replicated (see Tanaka et al., 2019 for a meta-analysis) and is considered to be a reliable indicator of being active in presence of a sequences of causal events.c However, some have questioned whether temporal binding is a specific marker of agency, or a more general principle of causal perception (Gutzeit et al., 2023; Hoerl et al., 2020; Kong et al., 2024).

Studies have shown that an increase of predictability of the action and the outcome produces stronger TB (i.e., the time was perceived as more compressed; Beck et al., 2017; Di Costa et al., 2018; Engbert & Wohlschläger, 2007; J. Moore & Haggard, 2008; J. W. Moore et al., 2009; but three studies reported no effect, or an effect in the opposite direction: Desantis et al., 2012; Haering & Kiesel, 2014; Majchrowicz & Wierzchoń, 2018). Regarding the contribution of intentionality on TB, studies have shown that contrasting being the author of the action (i.e., active experience), compared to not being the author (i.e., passive experience) of the action led to a weaker TB (Caspar et al., 2015; J. W. Moore & Obhi, 2012; Wiesing & Zimmermann, 2024; see Kong et al., 2024; Suzuki et al., 2019 for opposite findings). Further, several studies contrasting being the author of the decision, compared to not being the author of the decision (i.e., choosing what to do – free decisions – compared to being instructed on what to do) also weakened TB (Barlas, 2019; Caspar et al., 2016; Pech & Caspar, 2023). However, to the best of our knowledge, no study has investigated how the intention-action part interacts with the predictability of the outcome part. Our study thus aims at replicating findings on TB along intentionality, contrasting passive, instructed and free decisions. Manipulating both the authorship of the action and of the decision. We also aim at replicating findings on TB along causality, contrasting degree of predictability of the outcome. Finally, we want to provide new evidence regarding the interplay of intentionality and predictability, manipulating the intentionality conditions orthogonally with our predictability conditions.

The formation of intention prior a voluntary action has also been associated with a slow negative cortical potential measured through electro-encephalography – called the Readiness Potential (RP) or Bereischaftpotential (Kornhuber & Deecke, 2016; Libet et al., 1983; Schurger et al., 2021). A series of experiments have found that the RP seems to increase when choosing when to act rather than reacting to a cue (Jahanshahi et al., 1995; Jankelowitz & Colebatch, 2002; Khalighinejad et al., 2018) or choosing which action to perform rather than doing a pre-determined action (Dirnberger et al., 1998; Praamstra et al., 1995), suggesting an effect of intentionality on the RP.

This is consistent with findings that trace the origin of the RP in the Supplementary Motor Area (SMA; Shibasaki & Hallett, 2006). These regions have indeed been shown to be involved specifically for self-generated actions compared to externally cued actions (Passingham et al., 2010).

Interestingly, not only the presence of a choice (i.e., when or what to do) seems to influence the RP, but also the consequences of the action (i.e., what it is about). For instance, authors have found that the presence of an outcome (e.g., a tone), compared to its absence, lead to a diminished RP (Reznik et al., 2018; Vercillo et al., 2018; Wen et al., 2018; see VaezMousavi & Barry, 1993 for an opposite finding). Other studies have shown that having a defined goal to lead to an increased RP compared to not having a precise goal. For instance, having a to exert a specific amount of force (Masaki et al., 1998) or being able to earn extra money (McAdam & Seales, 1969; Pech et al., 2025), increases the RP compared to a control condition. Regarding the effect of the predictability of the outcome on the RP, we only found one study that investigate this effect (Travers et al., 2021). Participants performed a learning paradigm where they had to find when to act to obtain the desired outcome. The authors observed that participants had a lower RP in the initial guess (i.e., exploratory) trials when the outcome was less predictable than in the following planned (i.e., exploitative) trials when the outcome became more predictable. However, an alternative explanation is that the increased RP in the planned trials reflect a refinement of the goal as to when to act rather than the predictability of the outcome per se. As mentioned earlier, having a more precise goal to achieve seems to produce stronger RP. Hence, the question as to whether the predictability of the outcome – when the goal representation remains stable across the whole task – influences the RP still needs to be addressed. Furthermore, no studies investigated the interaction of the intentionality (i.e., when to act, and what to do) and of the predictability of the outcome on the RP.

Building on these theoretical and experimental foundations, the present study aims to address the role of the choice as to what and when to act (i.e., intentionality), the predictability of the outcome, and their interaction on the marker specifically associated with the prospective process (i.e., the RP) or the markers combining the prospective and retrospective process (i.e., reported SoA and the TB). We designed a task where the selection of a word (among 9 presented in a grid of 3x3, see Figure 1) produces the appearance of a related image. In a within-subject design, participants could either (1) decide which word to select (i.e., what to do), and when to select it (Free condition) or (2), were cued as to which word to select but free as to when to do it (Instructed condition) or (3), merely observed the selection of the word without making a movement (Passive condition).

These three experimental conditions make it possible to contrast both the source of the decision (i.e., Free condition compared to Instructed and Passive conditions), and the source of the action (i.e., Free and Instructed conditions compared to the Passive condition). We also orthogonally manipulated the predictability of the resulting image presented following the selection of the word. There was a phase of selection of the words, and then a phase of activation of the words with the associated image presented (see fig 1). The selected word always corresponded to the activated word (and presented image) in the Full Predictability condition. In the Medium Predictability condition, the activated word was randomly selected among the row of the selected word (i.e., 1/3 of the activated word corresponded to the selected one). Finally, in the Low Predictability condition, the activated word was randomly selected among the grid (i.e., 1/9 of the activated word corresponded to the selected one). We hypothesized that the different markers of volition (i.e., reported SoA, TB, and RP) would increase in the Free condition, compared to both the Instructed and Passive conditions (Caspar et al., 2018; Dirnberger et al., 1998; Jahanshahi et al., 1995; Khalighinejad et al., 2018; J. W. Moore & Obhi, 2012; Praamstra et al., 1995). We also hypothesized that they would increase when comparing the Instructed condition and the Passive condition. We further hypothesized that the different markers of volition would increase in the Full Predictability condition compared to both the Medium Predictability and Low Predictability conditions (Beck et al., 2017; Di Costa et al., 2018; Travers et al., 2021). In addition, these markers would also increase in the Medium Predictability condition compared to the Low Predictability condition. For the interaction between the dimensions of intentionality (i.e., Free, Instructed and Passive condition) and the dimensions of perceived causality (i.e, Full, Medium, Low Predictability conditions), we did not formulate a specific directional hypothesis.

Method

Participants

We recruited 51 participants through the credit system of the Université libre de Bruxelles. Participants were instructed to present themselves with hair conditions compatible with EEG recording (dry hair and no products that could interfere with the EEG). All participants were first-year students in the Faculty of Psychological and Educational Sciences and received study credits as compensation for their participation.

We first collected fifteen participants but had a problem on both the recording of the behaviour (for all of them) and of the electro-encephalography (EEG; for twelve of them). For the behaviour, we did not include the delay in the recorded files. Therefore, we could not analyse TB for all these fifteen participants, as the factor of delays could not be included. For the EEG, we had an initial problem with the triggers on the tenth first participants. Among the five others we had to remove two due to bad signals quality. Leaving use with three out of the first fifteen participants for the EEG data that we kept for the final sample. The first fifteenth behavioural data are available on OSF, as well as the last five EEG data (link).

We did not set a specific sample size in advance, but we aimed to recruit a maximum of 50 participants (due to time constraint) and a minimum of 20 participants (based on previous studies: Di Costa et al., 2018; Khalighinejad et al., 2018; Pech et al., 2025; Travers et al., 2021).

Procedure and Materials

The experiment comprised 396 trials arranged in nine experimental blocks, each block corresponding to a unique combination of two fully crossed within-participant factors: the source of action choice with different levels of intentionality (Passive, Instructed, or Free) and the predictability of the outcome with different levels of predictability (Low Predictability, Medium Predictability, or Full Predictability). Block order was randomised for every participant to minimise sequence effects. Ten semantic categories of photographs (e.g., animals, vegetables, vehicles …) were created, each containing ten items. On every trial, nine items—three drawn from each of three categories—were displayed simultaneously in a 3 × 3 grid and mapped to the nine keys of the right-hand numeric keypad (see Figure 1). A selected item immediately turned solid blue, and a 400-Hz tone (50ms) marked the subsequent outcome after a delay of 200, 500, or 800ms (pseudo-randomly selected).

Before beginning the main task, participants completed a short training session in which they freely chose displayed items, pressed the corresponding keys, then observed the squares turn blue, and heard the tone after each of the three delays. Following this, participants reported the perceived interval between the press and the tone on a 0–1000ms slider. Individual reaction time distributions gathered during the training were later used to schedule the automated selections in the Passive condition. Each experimental block contained 44 trials delivered as two 22-trial sequences in a pseudo-randomized order. Half of the trials required participants to rate their Sense of Agency (SoA) on a continuous 0–100 slider in response to statements such as “I felt control over the selection” (see supplementary S1 for more details on the list of questions). The remaining trials required them to estimate, on a 0–1000ms slider, the interval between the key press (or automatically triggered selection) and the tone. Whether the SoA sequence or the interval-estimation sequence appeared first was counter-balanced between participants.

The manipulation of action choice was implemented as follows. In the *Passive* condition participants rested the index finger on the central keypad key (i.e., 5); after a delay sampled from their own reaction-time distribution, one square turned blue. In the *Instructed* condition a blue outline cued a specific square, and participants pressed the corresponding key to turn it blue. In the *Free* condition the display was unmarked, and participants had between 300ms and 10s to select any item. Regardless of conditions, the tone and a picture appeared together after the randomly assigned delay (i.e., 200ms, 500ms or 800ms). Outcome predictability was manipulated orthogonally to action choice. Under Low Predictability the picture was chosen at random from the nine on-screen items (probability 1⁄9 of matching the selected item). tUnder Medium Predictability the picture was randomly selected from the same semantic category as the chosen item (probability 1⁄3 of a match). Under Full Predictability the picture was identical to the chosen item (probability 1/1 of a match). Participants were explicitly informed about the three modes of action (i.e., intentionality) choice but were not informed that outcome predictability varied across blocks. The total duration of the task was approximately 50 min.

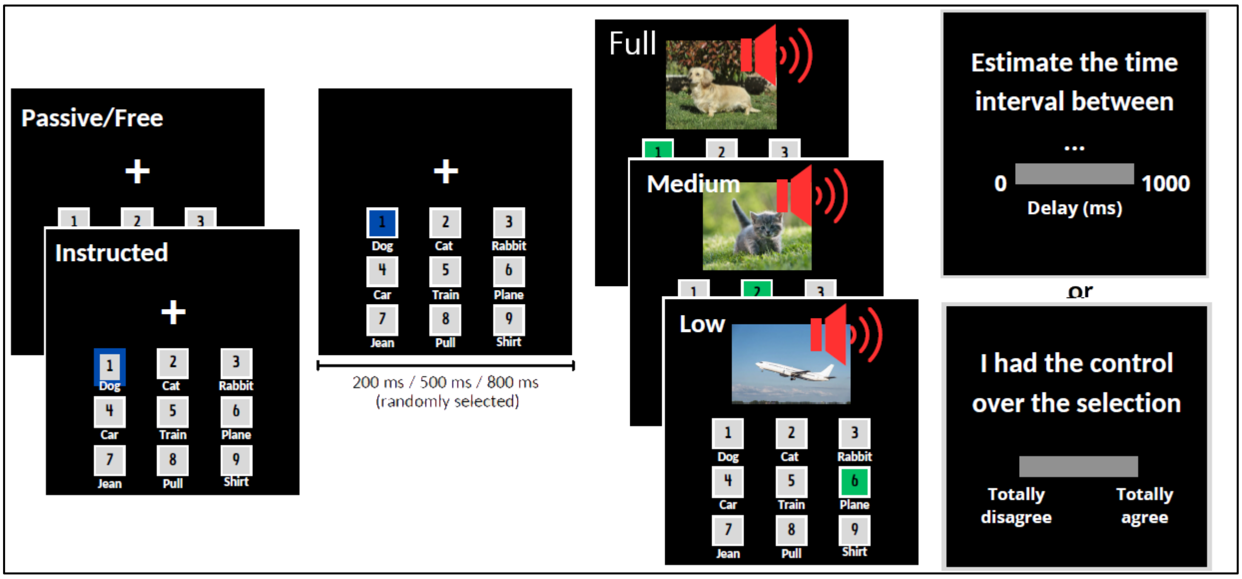

Figure 1| Design of the task. From left to right, depending on the level of intentionality, participants either viewed an unmarked grid (in the Passive and Free conditions) or a grid with one square outlined in blue (in the Instructed condition). In the Passive condition, no movement was required; after a delay sampled from a distribution matching each participant's reaction times (obtained during training), one of the squares was automatically selected and filled in blue. In the Free condition, participants were free to select any square by pressing the corresponding key. In the Instructed condition, participants were required to press the key corresponding to the highlighted square. In all conditions, once the square was selected—either automatically (Passive) or via key press (Free and Instructed)—it was filled in blue to confirm selection. Following a delay of 200ms, 500ms, or 800ms (randomly assigned), a picture was displayed, and a tone was played. The square corresponding to the picture was then filled in green. This image could be either fully predictable (identical to the selected item), moderately predictable (from the same semantic category and grid row), or minimally predictable (randomly selected from the *entire grid). Finally, participants either estimated the interval between the action (i.e., when the square turned blue) and the tone, or rated their SoA.*

EEG recordings and processing

EEG data were acquired at a sampling rate of 2,048 Hz from 64 channels, placed according the international 10-20 system, using the Biosemi system (see http://www.biosemi.com for hardware details). All data were recorded by the Actiview software. Due to error of recording while using Activew, 3 participants did not have the 64 electrodes recorded. We therefore had 39 participants remaining.

Data were processed using MNE-Python (Gramfort et al., 2013). We downsampled the data to 512 Hz using the default Fast Fourier Transform method of the resample() function in MNE-python. We then applied a bandpass filter between 0.1 and 40 Hz, with the Finite Impulse Response method, a zero-phase delay and the Hamming window (in line with other literature that measured the RP; Travers et al., 2021; Wen et al., 2018). We detected and interpolated bad channels automatically using the find_all_bads() function of the pyprep.NoisyChannels ($M = 2.7$, $SD = 2.5$) (Bigdely-Shamlo et al., 2015). This function uses a combination of criteria: "extreme amplitudes (deviation criterion), lack of correlation with any other channel (correlation criterion), lack of predictability by other channels (predictability criterion), and unusual high-frequency noise (noisiness criterion)" in addition to the random sample consensus method (Fischler & Bolles, 1987). After interpolating, a copy of the data was created in order to apply an Independent Component Analysis (ICA), with a high-pass filter of 1Hz. The high-pass filter of 1Hz allows an improvement of the performance of the ICA (Winkler et al., 2015). ICAs were computed with the number of components defined in order to represent 99.99% of the data. To detect eye movements (i.e., blink and saccades), we visually selected the components ($M = 2.1$, $SD = 0.3$) to remove from the original data, and the copy of the data was not further used. During the visualization of components, we also looked if participants had more than 32 components (out of 64 electrodes) as a quality check. ICA is a source separation technique, if fewer components were founded, we took this as a sign of long segment of noise remaining. For these participants (8/39), we annotate manually bad segments based on visual inspection, and reperformed the ICAs. If the ICAs had decomposed into fewer than 32 components, we did not keep those participants for further analysis (5/39).

We then re-referenced the channels using the reference-electrode standardization technique with a point at infinity with a head model and the forward method (Gramfort et al., 2013; Yao, 2001; Yao et al., 2019). The data were epoched on electrode Cz in a window from -3s to 1s around the hand press. We first used a baseline from -5ms to 5ms around the action onset (i.e. keypress in the

Instructed and Free condition, and the apparition of the selected word in the Passive condition) to avoid making any assumptions about the onset of the RP (Khalighinejad et al., 2018; Pech et al., 2025). However, we observed that the RP across participants and conditions was composed of a first negative shift until -0.5s, and a positive shift between -0.5s and 0s. A baseline on the action onset would affect the interpretation of the negative shift of the RP, as it will depend on the positive shift that follows. We therefore decided to use a baseline between -2.4s and -1.9s, to be close to the onset of the RP without including it into the baseline. This choice was based on visual inspection of the grand average but is also a baseline that is close from other studies (Khalighinejad et al., 2018, 2019; Parés-Pujolràs et al., 2019; Travers et al., 2021; Travers & Haggard, 2021). The literature has sometimes interpreted the RP as constituted of two components, an early part preceding -500ms and the last part from -500 to 0ms (Schurger et al., 2021; Shibasaki & Hallett, 2006). However, we did not expect the RP to have a positive shift in the late part. Few studies mention the existence of positive shifts in the RP (Jo et al., 2014; VaezMousavi & Barry, 1993). Altogether, we therefore decided to decompose the RP in two parts. An early part from -1,000ms to -500ms, and a late part from -500ms to 0ms before action onset guided by the literature and based on a visual inspection of the grand averages across all conditions and participants (see figure 4; Jahanshahi et al., 1995; Jankelowitz & Colebatch, 2002; Shibasaki & Hallett, 2006). We also extracted and analysed the slope of the early and late part of RP, which is not influenced by the selection of the baseline. Moreover, measuring the mean and the slope helps in getting more confidence in the results if they do converge. Epochs containing artifacts were rejected based on the value of the mean, the peak-to-peak magnitude, and the slope extracted in the period from -2.5s to 0s within each participant (see "Data exclusion" section below).

Statistical analysis

Our main analysis method relied on Bayesian linear mixed models, using the 'brms' R package (Bürkner, 2017). For each parameter we report the estimated medians (Med) and the 89% Highest Density Interval (HDI89%). Furthermore, for each comparison we report the estimated medians difference (Meddiff), the 89% Highest Density Interval (HDI89%; Kruschke, 2018; Makowski et al., 2019; McElreath, 2016), the Probability Direction (PD; Kruschke, 2018; Makowski et al., 2019), the Bayes Factor in favor of H1 (BF10 > 3 in favor of H1, BF10 < 1/3 in favor of H0; Dienes, 2014; Kruschke, 2018; Makowski et al., 2019), and the Robustness Range that leads to the same Bayes Factor conclusion (e.g. RRH0 if BF10 < 1/3 or RRIN if 1/3<BF10<3; Dienes, 2014, 2019). See Supplementary S2 Statistical Analysis for further information. Note that the PD is roughly equivalent to a p-value (Makowski et al., 2019; Shi & and Yin, 2021). Hence, a p-value of 0.05 would correspond to a PD of 97.5% for a two-sided test, and to a PD of 95% for a one-sided test.

For each parameter we report the estimated medians (Med) and the 89% Highest Density Interval (HDI89%). Furthermore, for each comparison we report the estimated medians difference (Meddiff), the 89% Highest Density Interval (HDI89%), the Probability Direction (PD), the Bayes Factor in favor of H1 (BF10), and the Robustness Range that leads to the same Bayes Factor conclusion (e.g. RRH0 if BF10 < 1/3 or RRIN if 1/3<BF10<3).

a) *Data exclusion*

We wanted participants to pay attention to the selection, trials in which the RTs were faster than 350ms were then discarded (Cohen & Donner, 2013; Pech et al., 2024; Pech & Caspar, 2022; Semmelmann & Weigelt, 2017). Overall, this resulted in the rejection of 4.4% of trials (SD = 4.3%) for all our dependent variables (i.e., questions, interval estimations and RP).

We also removed trials that were outliers within each participant, due to behavioural or EEG data. We used the Inter-Quartile Range (IQR) method with a threshold of 2 IQR below the 25th percentile, and above the 75th percentile to demarcate outliers (Hoaglin et al., 1986; Jones, 2019; Leys et al., 2013; Osborne & Overbay, 2019). This method rejected 4.0% of trials (SD = 2.6%) for the RTs, 8.4% (SD = 3.5%) for the RP, and 1.0% (SD = 1.4%) for the TB.

In addition to removing outlier trials within participants, we also removed participants' that were outliers. For the TB measure, we wanted to ensure that participants correctly discriminated the three durations of the delays (i.e., 200ms, 500ms, 800ms). We set up a contrast with -1, 0, 1 for the 200 ms, 500ms, and 800ms delays, respectively. We then performed a linear regression analysis using the 'lm()' function in R with interval estimate as an outcome, and the three delays as a predictor, for each participant separately. We only kept participants with a significant positive linear trend (i.e., p<.05) for the contrast across the delays (similarly as: Caspar et al., 2016, 2018; Pech et al., 2025; Pech & Caspar, 2022).. This resulted in the removal of 6/36 (17%) participants. We also removed participants who were outliers using the 2IQR method on each measurement (Pech et al., 2025; Pech & Caspar, 2025). We calculated the between participants' outliers on the estimate slope of the models representing the difference between conditions (e.g., Instructed condition minus Passive condition; see supplementary for more details S2). Based on this method, we removed 1/36 participants for the reported SoA, 4/23 participants for the reported Deliberation, 2/50 participants for the slope of the RP, 9/36 participants for the early part of the RP, 3/36 for the late part of the RP, and 1/30 participants for the TB (6 were already removed due to the absence of significant linear trend).

b) Sense of Agency (SoA) questions

We calculated Cronbach's alpha over the 10 questions to ensure inter-item reliability. To do so, we used the 'cronbach.alpha()' function of the ltm library in R (Rizopoulos, 2007), with 1,000 bootstraps and 89% confidence interval. A value above 0.7 is usually taken as evidence for reliability (Tavakol & Dennick, 2011). We found evidence for reliability between the 10 questions ($\alpha = 0.875$, CI89% = [0.859 0.889]). The questions were thus aggregated into a single score of Sense of Agency (SoA); the score was the average of the 10 questions.

Results

This section shows the results for the reported SoA, the TB, and the RP. For each of these measurements, different models were computed, which are accessible in Supplementary Information S3, with Figure 2 for self-reports, Figure 3 for TB, and Figures 4-5 for the RP. We used a model with a Gaussian family distribution, an identity link for both mu and sigma for all the models (see Supplementary Information S3 for more information). We included the interaction of intentionality (Passive, Instructed, and Free conditions) and predictability (Low, Medium, Full Predictability conditions) along with their main effects, as fixed effects. Participants were included as random intercepts. Finally, the main effects, as well as their interaction, were included as random slopes per participant. This was the minimum structure of all the models, except if stated, it was the model use.

Self-Reported Sense of Agency:

We analysed the self-reported Sense of Agency (SoA) ratings (from 0 = "I totally disagree l" to 100 = "I totally agree")

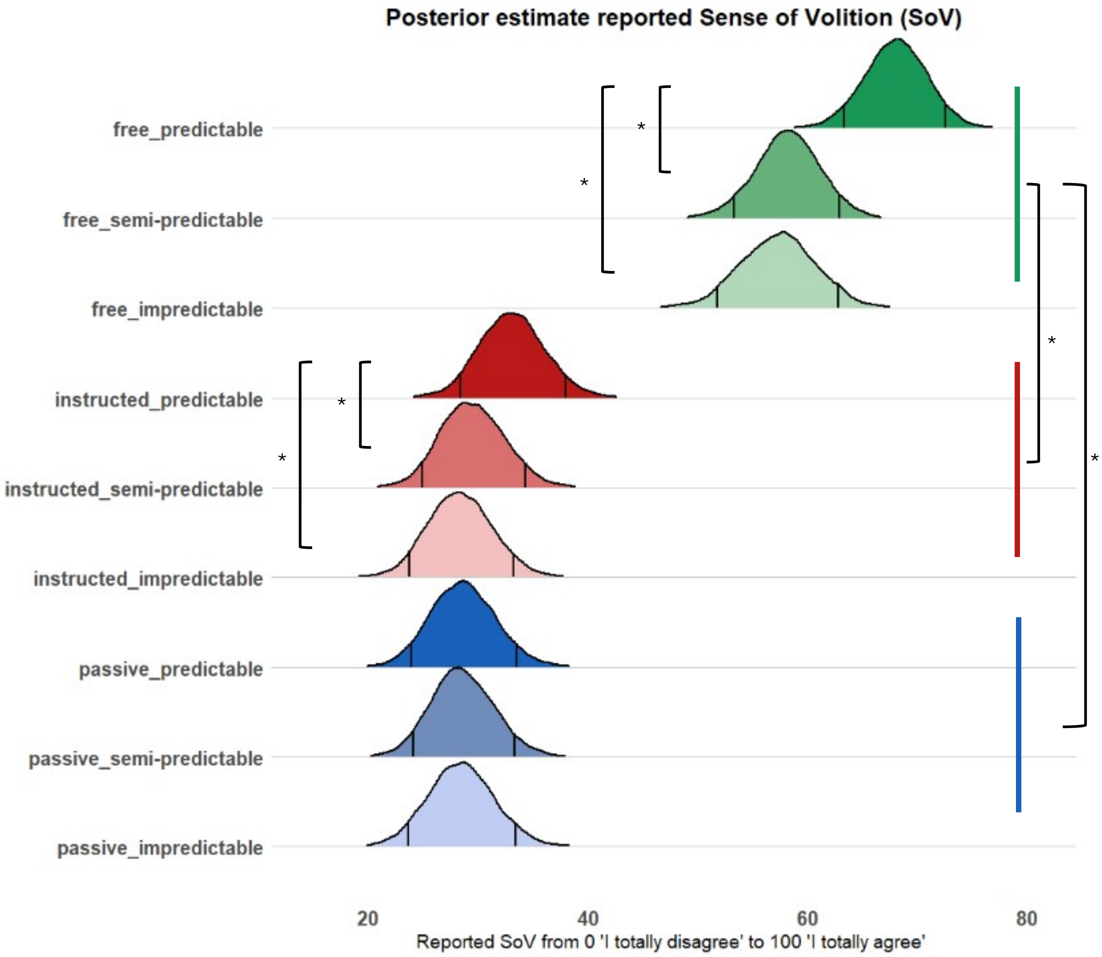

Figure 2

Results are averaged over levels of Intentionality (i.e.,Passive, Instructed, and Free). For the Passive condition (Med = 28.4, HDI89% = [23.3 34.0]), there was inconclusive evidence for similar SoA with the Instructed condition (Med = 30.2, HDI89% = [25.0 35.7]; Meddiff = 1.8, HDI89% [-1.2 4.6], PD = 83.4%, BF10 = 0.59, RRIN = [0.9 9.4]). There was evidence for higher SoA in the Free condition (Med = 61.2, HDI89% = [56.0 66.4]) compared to both the Passive condition (Med = 28.4, HDI89% = [23.3 34.0]; Meddiff = 32.6, HDI89% [27.0 38.1], PD = 100%, BF10 = 1.93e+16, RRH1 = [<5 2321]), and the Instructed condition (Med = 30.2, HDI89% = [25.0 35.7]; Meddiff = 30.9, HDI89% [26.0 36.0], PD = 100%, BF10 = 1.12e+16, RRH1 = [<5 2164]).

Results are averaged over levels of Causality (i.e., Low Predictability, Medium Predictability, and Full Predictability). For the Low Predictability condition (Med = 38.0, HDI89% = [33.5 43.0]), there was evidence for similar SoA with the Medium Predictability condition (Med = 38.6, HDI89% = [34.6 43.2]; Meddiff = 0.7, HDI89% [-1.4 2.8], PD = 71.0%, BF10 = 0.29, RRH0 = [4.3 5]). There was evidence for higher SoA in the Full Predictability condition (Med = 43.2, HDI89% = [39.2 47.7]) compared to both the Low Predictability condition (Med = 38.0, HDI89%

= [33.5 43.0]; Meddiff = 5.2, HDI89% [2.8 7.5], PD = 99.9%, BF10 = 75.15, RRH1 = [<5 116]), and the Medium Predictability condition (Med = 38.6, HDI89% = [34.6 43.2]; Meddiff = 4.5, HDI89% [2.5 6.4], PD = 100.0%, BF10 = 71.1, RRH1 = [<5 116]).

These results were largely consistent when looking at the interaction between Intentionality and Causality (see the section S2 Results in the supplementary for all tables). However, in the Passive condition, we observed inconclusive evidence for similarity between the Full Predictability condition (Med = 28.6, HDI95% = [22.7 34.4]) and both the Low Predictability condition (Med = 28.4, HDI95% = [22.7 34.7]; Meddiff = 0.162, HDI95% [-3.623 3.566], PD = 52.99%, BF10 = 0.47, RRIN = [3.527 7.087]), and the Medium Predictability condition (Med = 28.5, HDI95% = [23.1 34.4]; Meddiff = 0.076, HDI95% [-3.078 3.429], PD = 51.37%, BF10 = 0.40, RRIN = [4.056 6.164]). For the Instructed condition, we observed evidence for higher SoA in the Full Predictability condition (Med = 33.0, HDI95% = [27.5 39.4]) compared to both the Low Predictability condition (Med = 28.3, HDI95% = [22.8 34.5]; Meddiff = 4.692, HDI95% [1.353 8.139], PD = 98.56%, BF10 = 4.75, RRH1 = [<5 8.149]), and inconclusive for the Medium Predictability condition (Med = 29.4, HDI95% = [24.1 35.6]; Meddiff = 3.602, HDI95% [0.641 6.539], PD = 97.47%, BF10 = 2.21, RRH1 = [3.5 35.3]). For the Free condition, SoA also increased with predictability. Specifically, there was evidence for higher SoA in the Full Predictability condition (Med = 68.0, HDI95% = [62.3 73.6]) compared to both the Low Predictability condition (Med = 57.4, HDI95% = [50.5 64.0]; Meddiff = 10.684, HDI95% [5.458 15.981], PD = 99.87%, BF10 = 77.07, RRH1 = [<5 116]), and the Medium Predictability condition (Med = 58.2, HDI95% = [52.4 64.1]; Meddiff = 9.826, HDI95% [5.966 13.277], PD = 100%, BF10 = 777.84, RRH1 = [<5 329]).

Resume results reported SoA

We observed evidence for higher reported SoA in the Free condition compared to both the Instructed and Passive conditions. The latter two did not differ from each other. We also observed that in both the Free and Instructed conditions, SoA was higher in the Full Predictability condition compared to both the Low Predictability and the Medium Predictability conditions, which was not the case in the Passive condition.

Temporal Binding

Different delays were used in the procedure between the action and the outcome. This different delays seems to produces variation at least on the effect of intentionality on the TB (Caspar et al., 2016; Kong et al., 2024; Pech et al., 2025; Wiesing & Zimmermann, 2024). Therefore, we added the actual delays (i.e., 200ms, 500ms, and 800ms) as a fixed effect, as well as in interaction with intentionality and causality in the model. The fixed effect and their interaction were also added as random slopes per participants. However, we removed the correlation between the random intercepts and the random slopes to reduce the complexity of the model. Moreover, a previous study have shown an effect of reaction times on the TB (Pech et al., 2025), it was therefore added (scaled and centred) as a fixed effect to the model. We analysed the Temporal Binding (TB) effect using interval estimation (in ms), where shorter interval estimations reflect stronger TB.

Results are averaged over levels of Intentionality. For the Passive condition (Med = 382 ms, HDI95% = [343 416]), there was evidence for stronger TB (i.e., shorter interval estimates) compared to the Instructed condition (Med = 402 ms, HDI95% = [367 436]; Meddiff = 19.851 ms, HDI95% [1.629 37.774], PD = 95.90%, BF10 = 3.20, RRH1 = [<15 16.084]). We observed inconclusive evidence for similar TB between the Instructed condition and the Free condition (Med = 394 ms, HDI95% = [358 428]; Meddiff = -8.023 ms, HDI95% [-22.409 5.884], PD = 81.23%, BF10 = 0.93, RRIN = [4.272 42.721]). Finally, there was inconclusive evidence for similar TB between the Passive and Free conditions (Meddiff = 11.885 ms, HDI95% [-10.419 33.011], PD = 81.01%, BF10 = 1.29, RRIN = [6.493 60.555]).

Results are averaged over levels of Causality. For the Low Predictability condition (Med = 407 ms, HDI89% = [377 436]), there was inconclusive evidence for similar TB compared to the Medium Predictability condition (Med = 398 ms, HDI89% = [370 426]; Meddiff = -9.482 ms, HDI89% [-26.992 8.592], PD = 80.24%, BF10 = 1.05, RRIN = [4.912 45.808]). There was evidence for stronger TB in the Full Predictability condition (Med = 373 ms, HDI89% = [343 401]) compared to both the Low Predictability condition (Meddiff = -34.106 ms, HDI89% [-53.967 -13.315], PD = 99.48%, BF10 = 27.56, RRH1 = [<15 150]) and the Medium Predictability condition (Meddiff = -24.587 ms, HDI89% [-37.611 -11.781], PD = 99.79%, BF10 = 30.71, RRH1 = [<15 161]).

These results were consistent when looking at the interaction between Intentionality and Causality. And also, when looking at the interaction between Intentionality, Causality and Actual Delays (see the section S2 Results in the supplementary for all tables).

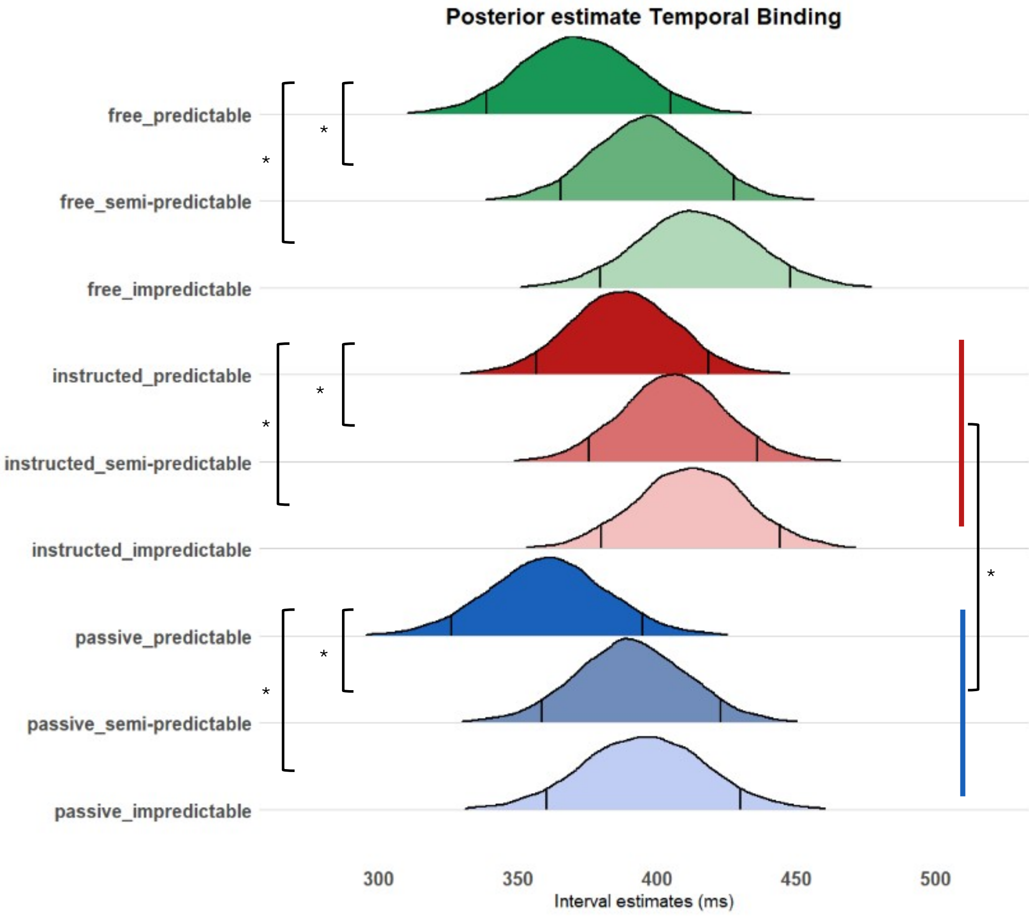

Figure 3

Resume results TB

To resume, the TB was consistently higher when the action and the consequences matched consistently (i.e., Full Predictability condition) compared to when it did not match systematically (i.e., Low and Medium Predictability conditions). Finally, we observed that the Passive condition produces a stronger TB compared to the Instructed condition.

Readiness Potential:

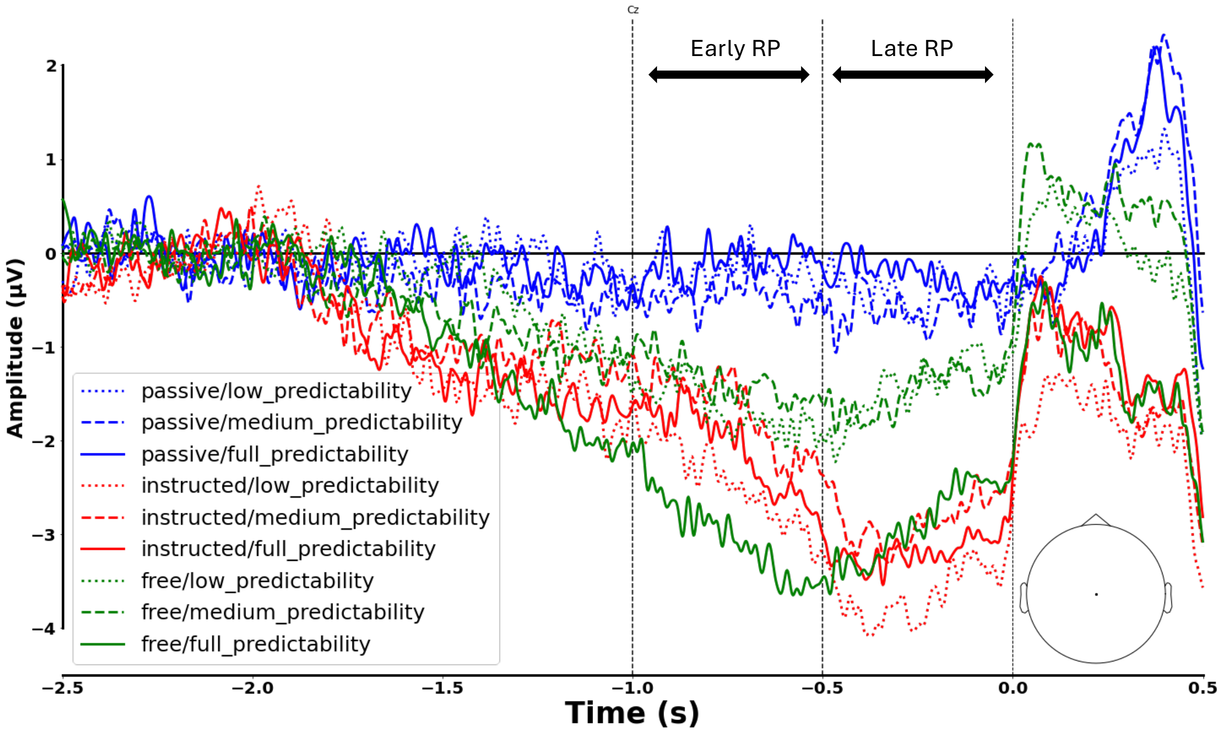

Figure 4. EEG plot of the RP on the Cz electrode, time locked on the keypress. Each line represents a condition. The full lines represent the Full Predictability conditions, the dashed lines represent the Medium Predictability condition, and the dotted lines represent the Low Predictability conditions. The blue lines represent the Passive conditions, the Red the Instructed conditions, and the Green the Free conditions.

Early RP

		Low Previsibility			Medium Previsibility			Full Previsibility		
		Passive	Instructed	Free	Passive	Instructed	Free	Passive	Instructed	Free
Mean RP	Median	-0,334	-2,384	-1,347	-0,531	-1,755	-0,896	0,011	-1,967	-2,604
	HDI89%	[-1.181 0.453]	[-3.192 -1.577]	[-2.278 -0.316]	[-1.284 0.201]	[-2.605 -0.952]	[-1.906 0.08]	[-0.772 0.822]	[-2.913 -1.027]	[-3.4 -1.776]
Slope RP	Median	-0,152	-2,767	-0,908	-0,183	-2,498	-1,584	-0,016	-2,621	-2,367
	HDI89%	[-1.39 1.031]	[-4.15 -1.394]	[-2.4 0.55]	[-1.39 0.969]	[-3.83 -1.096]	[-3.05 -0.226]	[-1.22 1.294]	[-3.95 -1.204]	[-3.7 -0.984]

Late RP

		Low Previsibility			Medium Previsibility			Full Previsibility		
		Passive	Instructed	Free	Passive	Instructed	Free	Passive	Instructed	Free
Mean RP	Median	-0,603	-3,222	-1,144	-0,662	-2,485	-1,238	-0,442	-2,8	-2,61
	HDI89%	[-1.5 0.235]	[-4.14 -2.317]	[-2.13 -0.119]	[-1.46 0.185]	[-3.38 -1.567]	[-2.22 -0.15]	[-1.27 0.418]	[-3.78 -1.859]	[-3.55 -1.754]
Slope RP	Median	-0,414	0,562	1,712	-0,092	0,248	0,942	-0,801	0,468	2,651
	HDI89%	[-1.529 0.763]	[-0.705 1.74]	[0.406 3.023]	[-1.177 0.952]	[-0.878 1.343]	[-0.249 2.221]	[-1.963 0.286]	[-0.728 1.614]	[1.458 3.974]

Figure 5.Resume of the estimates (in µV) of the early and late RP within each condition, as well as the HDI89%. For both the mean and the slope.

A previous study has shown an effect of reaction times on the TB (Pech et al., 2025), it was therefore added (scaled and centred) as a fixed effect to the model.

Mean early RP

We analysed the mean early Readiness Potential (RP; in μV). The RP values were baseline-corrected between -2.4s and -1.9s, therefore more negative values indicate stronger early RP activity.

Results are averaged over levels of Intentionality (i.e., Passive, Instructed, and Free). For the Passive condition (Med = -0.288 μV, HDI95% = [-0.975 0.434]), there was evidence for a weaker (i.e., less negative) mean early RP compared to both the Instructed condition (Med = -2.043 μV, HDI95% = [-2.895 -1.164]; Meddiff = -1.755 μV, HDI95% [-2.472 -1.025], PD = 99.99%, BF10 = 4.01e+2, RRH1 = [<1 46.416]), and the Free condition (Med = -1.622 μV, HDI95% = [-2.526 -0.706]; Meddiff = -1.330 μV, HDI95% [-2.141 -0.566], PD = 99.67%, BF10 = 16.79, RRH1 = [<1 5.722]). For the Instructed condition (Med = -2.043 μV, HDI95% = [-2.895 -1.164]), there was inconclusive evidence for a similar mean early RP compared to the Free condition (Meddiff = 0.426 μV, HDI95% [-0.189 1.064], PD = 85.89%, BF10 = 0.76, RRIN = [0.248 2.310]).

Results are averaged over levels of Causality (i.e., Full Predictability condition, Medium Predictability condition, and Low Predictability condition). For the Low predictability condition (Med = -1.360 μV, HDI95% = [-2.120 -0.604]), there was inconclusive evidence for a similar RP with both the Medium predictability condition (Med = -1.070 μV, HDI95% = [-1.800 -0.262]; Meddiff = 0.294 μV, HDI95% [-0.209 0.817], PD = 81.98%, BF10 = 0.49, RRIN = [0.163 1.520]), and the Full predictability condition (Med = -1.530 μV, HDI95% = [-2.270 -0.805]; Meddiff = -0.169 μV, HDI95% [-0.706 0.396], PD = 68.60%, BF10 = 0.38, RRIN = [0.123 1.150]). We also observed inconclusive evidence for similarity between the Medium Predictability condition (Med = -1.070 μV, HDI95% = [-1.800 -0.262]) and the Full predictability condition (Meddiff = -0.461 μV, HDI95% [-0.976 0.072], PD = 92.03%, BF10 = 0.90, RRIN = [0.285 2.848]).

These results were consistent when looking at the interaction between Intentionality and Causality. The only difference emerged when comparing the Free condition across levels of Causality. We observed evidence for a stronger RP (more negative) in the Full predictability condition (Med = -2.604 μV, HDI95% = [-3.600 -1.596]) compared to both the Low predictability condition (Med = -1.347 μV, HDI95% = [-2.570 -0.145]; Meddiff = -1.255 μV, HDI95% = [-2.285 -0.121], PD = 96.61%, BF10 = 3.61, RRH1 = [<1 1.233]) and the Medium predictability condition (Med = -0.896 μV, HDI95% = [-2.090 0.336]; Meddiff = -1.710 μV, HDI95% = [-2.740 -0.682], PD = 99.62%, BF10 = 17.96, RRH1 = [<1 6.136]).

Slope early RP

We analysed the early slope of the Readiness Potential (RP; in µV). The slope with more negative values indicating a steeper (i.e., stronger) early RP buildup.

Results are averaged over levels of Intentionality. For the Passive condition (Med = -0.111 µV, HDI95% = [-1.200 0.982]), there was evidence for a weaker early RP slope compared to both the Instructed condition (Med = -2.629 µV, HDI95% = [-4.040 -1.205]; Meddiff = -2.505 µV, HDI95% = [-3.845 -1.042], PD = 99.58%, BF10 = 6.79e+1, RRH1 = [<0.5 11.551]), and the Free condition (Med = -1.623 µV, HDI95% = [-3.140 -0.239]; Meddiff = -1.512 µV, HDI95% = [-2.826 0.015], PD = 95.20%, BF10 = 7.15, RRH1 = [<0.5 1.239]). For the Instructed condition (Med = -2.629 µV, HDI95% = [-4.040 -1.205]), there was evidence for a stronger early RP slope compared to the Free condition (Med = -1.623 µV, HDI95% = [-3.140 -0.239]; Meddiff = 1.005 µV, HDI95% = [0.193 1.857], PD = 97.25%, BF10 = 6.37, RRH1 = [<0.5 1.155]).

Results are averaged over levels of Causality (i.e., Low Predictability, Medium Predictability, and Predictable). For the Low predictability condition (Med = -1.270 µV, HDI95% = [-2.490 -0.163]), there was inconclusive evidence for a similar early RP slope compared to the Medium predictability condition (Med = -1.420 µV, HDI95% = [-2.580 -0.268]; Meddiff = -0.139 µV, HDI95% = [-1.009 0.677], PD = 60.56%, BF10 = 1.11, RRIN = [0.176 1.756]) and compared to the Full predictability condition (Med = -1.670 µV, HDI95% = [-2.780 -0.462]; Meddiff = -0.397 µV, HDI95% = [-1.258 0.533], PD = 75.83%, BF10 = 1.48, RRIN = [0.232 2.321]). For the Medium predictability condition (Med = -1.420 µV, HDI95% = [-2.580 -0.268]), there was also inconclusive evidence for a similar early RP slope compared to the Full predictability condition (Meddiff = -0.250 µV, HDI95% = [-1.106 0.575], PD = 68.51%, BF10 = 1.26, RRIN = [0.202 1.882]).

When looking at the interaction between Intentionality and Causality, we observed that the difference in early RP slope between the Instructed and Free conditions progressively diminished as predictability increased. Specifically, there was evidence for a stronger RP slope in the Instructed condition compared to the Free condition in the Low predictability condition (Meddiff = 1.837 µV, HDI95% = [0.538 3.263], PD = 98.37%, BF10 = 1.52e+1, RRH1 = [<0.5 2.489]), while in the Medium predictability condition this difference became at the edge of being inconclusive (Meddiff = 0.910 µV, HDI95% = [-0.350 2.178], PD = 87.43%, BF10 = 3, RRIN = [0.500 4.663]), and in the Full predictability condition, the difference further diminished with inconclusive evidence (Meddiff = 0.253 µV, HDI95% = [-1.092 1.617], PD = 61.34%, BF10 = 1.80, RRIN = [0.286 2.861]). This is due to the increase of the slope of the RP in the Free condition when the levels of Causality increases. Within the Free condition, we observed evidence for a stronger early RP slope (more negative) in the Full predictability condition (Med = -2.367 μV, HDI95% = [-4.190 -0.765]) compared to both the Low predictability condition (Med = -0.908 μV, HDI95% = [-2.650 0.993]; Meddiff = -1.465 μV, HDI95% = [-3.030 0.013], PD = 93.47%, BF10 = 5.64, RRH1 = [<0.5 1.005]), and inconclusively to the Medium predictability condition (Med = -1.584 μV, HDI95% = [-3.340 0.111]; Meddiff = -0.783 μV, HDI95% = [-2.214 0.547], PD = 81.92%, BF10 = 2.55, RRIN = [0.406 4.056]).

Mean late RP:

We analysed the mean early Readiness Potential (RP; in μV). The RP values were baseline-corrected between -2.4s and -1.9s, therefore more negative values indicate stronger early RP activity.

Results are averaged over levels of Intentionality. For the Passive condition (Med = -0.574 μV, HDI95% = [-1.330 0.240]), there was evidence for a weaker (i.e., less negative) late RP compared to both the Instructed condition (Med = -2.838 μV, HDI95% = [-3.780 -1.912]; Meddiff = -2.271 μV, HDI95% = [-3.005 -1.480], PD = 100%, BF10 = 2.31e+10, RRH1 = [<1 93.260]), and the Free condition (Med = -1.662 μV, HDI95% = [-2.610 -0.665]; Meddiff = -1.088 μV, HDI95% = [-1.896 -0.269], PD = 98.33%, BF10 = 4.42, RRH1 = [<1 1.520]). For the Instructed condition (Med = -2.838 μV, HDI95% = [-3.780 -1.912]), there was evidence for a stronger (i.e., more negative) late RP compared to the Free condition (Med = -1.662 μV, HDI95% = [-2.610 -0.665]; Meddiff = 1.181 μV, HDI95% = [0.576 1.811], PD = 99.66%, BF10 = 25.41, RRH1 = [<1 8.697]).

Results are averaged over levels of Causality. For the Low predictability condition (Med = -1.650 μV, HDI95% = [-2.530 -0.825]), there was inconclusive evidence for a similar RP compared to the Medium predictability condition (Med = -1.470 μV, HDI95% = [-2.300 -0.587]; Meddiff = 0.189 μV, HDI95% = [-0.341 0.780], PD = 70.79%, BF10 = 0.39, RRIN = [0.132 1.233]), and also inconclusive evidence for a similar RP compared to the Full predictability condition (Med = -1.950 μV, HDI95% = [-2.750 -1.135]; Meddiff = -0.294 μV, HDI95% = [-0.881 0.326], PD = 78.14%, BF10 = 0.52, RRIN = [0.163 1.630]). Additionally, there was inconclusive evidence for a similar RP when comparing the Medium Predictability condition (Med = -1.470 μV, HDI95% = [-2.300 -0.587]) to the Full predictability condition (Meddiff = -0.487 μV, HDI95% = [-1.071 0.075], PD = 91.01%, BF10 = 0.86, RRIN = [0.266 2.656]).

When looking at the interaction between Intentionality and Causality, we observed that the difference in early RP slope between the Instructed and Free conditions progressively diminished as predictability increased. For the Low predictability condition, we observed evidence for a stronger RP (more negative) in the Instructed condition (Med = -3.222 μV, HDI95% = [-4.350 -2.119]) compared to the Free condition (Med = -1.144 μV, HDI95% = [-2.410 0.084]; Meddiff = 2.089 μV, HDI95% [1.035 3.046], PD = 99.96%, BF10 = 2.11e+2, RRH1 = [<1 37.649]). For the Medium predictability condition, there was a weaker evidence for a stronger RP in the Instructed condition (Med = -2.485 μV, HDI95% = [-3.640 -1.421]) compared to the Free condition (Med = -1.238 μV, HDI95% = [-2.490 0.056]; Meddiff = 1.240 μV, HDI95% [0.309 2.197], PD = 98.03%, BF10 = 5.03, RRH1 = [<1 1.748]). However, in the Full predictability condition, there was inconclusive evidence for a similar RP between the Instructed condition (Med = -2.801 μV, HDI95% = [-3.950 -1.583]) and the Free condition (Med = -2.611 μV, HDI95% = [-3.720 -1.494]; Meddiff = 0.199 μV, HDI95% [-0.800 1.256], PD = 62.49%, BF10 = 0.68, RRIN = [0.215 2.154]).

When focusing on the Free condition across Causality levels, there was evidence for a stronger RP in the Full predictability condition (Med = -2.611 μV, HDI95% = [-3.720 -1.494]) compared to both the Low predictability condition (Med = -1.144 μV, HDI95% = [-2.410 0.084]; Meddiff = -1.469 μV, HDI95% [-2.605 -0.430], PD = 98.26%, BF10 = 6.41, RRH1 = [<1 2.154]), and the Medium predictability condition (Med = -1.238 μV, HDI95% = [-2.490 0.056]; Meddiff = -1.370 μV, HDI95% [-2.402 -0.304], PD = 97.96%, BF10 = 5.42, RRH1 = [<1 1.874]).

Slope Late RP:

We analysed the early slope of the Readiness Potential (RP; in μV). The slope with more positive values indicating a steeper (i.e., stronger) late RP buildup.

Results are averaged over levels of Intentionality. For the Passive condition (Med = -0.438 μV, HDI95% = [-1.413 0.524]), there was inconclusive evidence for a similar slope compared to the Instructed condition (Med = 0.432 μV, HDI95% = [-0.751 1.541]; Meddiff = 0.878 μV, HDI95% [-0.236 1.993], PD = 88.98%, BF10 = 2.94, RRIN = [0.466 4.663]). There was evidence for a steeper slope in the Free condition (Med = 1.774 μV, HDI95% = [0.478 2.964]) compared to both the Passive condition (Med = -0.438 μV, HDI95% = [-1.413 0.524]; Meddiff = 2.208 μV, HDI95% [0.958 3.447], PD = 99.72%, BF10 = 65.01, RRH1 = [<1 11.551]) and the Instructed condition (Med = 0.432 μV, HDI95% = [-0.751 1.541] ; Meddiff = 1.336 μV, HDI95% [0.378 2.346], PD = 98.00%, BF10 = 12.68, RRH1 = [<1 2.164]).

Results are averaged over levels of Causality. For the Low predictability condition (Med = 0.614 μV, HDI95% = [-0.394 1.670]), there was inconclusive evidence for a similar slope compared to both the Medium predictability condition (Med = 0.367 μV, HDI95% = [-0.610 1.330]; Meddiff = -0.244 μV, HDI95% [-1.027 0.569], PD = 69.67%, BF10 = 1.12, RRIN = [0.176 1.756]), and the Full predictability condition (Med = 0.772 μV, HDI95% = [-0.193 1.720]; Meddiff = 0.163 μV, HDI95% [-0.747 1.023], PD = 62.03%, BF10 = 1.13, RRIN = [0.176 1.756]). There was also inconclusive evidence for a similar slope between the Medium Predictability condition (Med = 0.367 μV, HDI95% = [-0.610 1.330]) and the Full Predictability condition (Meddiff = 0.408 μV, HDI95% [-0.378 1.223], PD = 79.27%, BF10 = 1.43, RRIN = [0.232 2.164]).

These results were consistent when looking at the interaction between Intentionality and Causality. The only difference emerged when comparing the Free condition across levels of Causality. There was inconclusive evidence for a steeper slope in the Full predictability condition (Med = 2.651 μV, HDI95% = [1.132 4.276]) compared to both the Low predictability condition (Med = 1.712 μV, HDI95% = [0.115 3.310]; Meddiff = 0.959 μV, HDI95% [-0.546 2.336], PD = 85.65%, BF10 = 3.29, RRIN = [0.500 0.575]) and conclusive evidence against the Medium predictability condition (Med = 0.942 μV, HDI95% = [-0.566 2.501]; Meddiff = 1.726 μV, HDI95% [0.364 3.021], PD = 97.94%, BF10 = 1.27e+1, RRH1 = [<0.5 2.164]).

Resume RP

To resume, the Early and Late part of the RP show more negativity for the Instructed and Free condition compared to the Passive condition – as expected due to absence of movement in the Passive condition. Additionally, we observed some evidence that there is more negativity in the Instructed condition compared to the Free condition. However, this difference vanishes when the levels of Causality increase, more precisely we do not observe such evidence in the Full predictability condition.

Surprisingly, for the late part of the RP, we observe a positive slope that was higher in the Instructed and the Free condition compared to the Passive condition – while we predicted a negative slope. Moreover, the slope of the late RP was steeper (i.e., more positive) in the Free condition compared to the Instructed. As well as steeper in the Full Predictability condition of the Free condition compared to the other levels of predictability.

Taken together, the negative component of the RP was more pronounced in the Instructed than the Free condition when outcome where not fully predictable, and the late positive component of the

RP was more pronounced in the Free condition compared to the Instructed condition. Both the early and late component seems sensitive to the predictability in the Free condition.

Discussion

This study had two main objectives. First, we wanted to replicate previously documented effects of intentionality and of outcome predictability on the markers of volition. We focused on a direct measure (the subjective sense of agency), on an indirect measure (temporal binding) and on a neural marker (the readiness potential). Second, we were specifically interested in orthogonally manipulating the relationships between intentionality and predictability so as to explore their respective contributions and their interactions on our markers volition. In our paradigm, participants could either choose which word to select to make the corresponding image appears (i.e., Free condition) or were instructed on which to choose but still performed the action (i.e., Instructed condition), or were passively watching the selection of the word (i.e., Passive condition). Within each of these conditions, we also manipulated the predictability of the image occurring, which either corresponds to the selected word (i.e., Full Predictability condition), or had either one out of three chances to correspond to it (i.e., Medium Predictability condition), or one out of nine chances (i.e., Low Predictability condition). Our results indicates that the reported Sense of Agency (SoA) and the Readiness Potential (RP) were more sensitive to the manipulation of the intention than of the predictability of the outcome. This effect on the predictability of the outcome was found when participants had to perform the action for the reported SoA (i.e., Instructed and Free conditions), but only when they both decide what to do and when to act for the RP (i.e., Free condition). However, the TB seems more sensitive to the manipulation of the predictability of the outcome.

Self-reports

In line with our first hypothesis, we observed higher score of reported SoA in the Free condition than in the Instructed or Passive conditions. However, contrary to our hypothesis we did not observe difference between the Instructed and Passive conditions. These results suggest that the SoA in our task was better explained as to choose what to do than merely producing the action. Several studies found similar results comparing instructed and free decision, with the later leading to a higher reported SoA (Barlas, 2019; Barlas et al., 2017; Caspar et al., 2016, 2020, 2022; Pech & Caspar, 2023; Yavuz et al., 2025). It is in line with the idea that the SoA is stronger when we are the author of the action, but also of the choice made. Interestingly, we did not observe difference between the Instructed and Passive condition, which contradict with the finding of Caspar and colleagues (2016). In their study, the participants focused on the feeling of responsibility related to the consequences, while we were targeting SoA more globally. This could suggest that when participants are instructed what to do, they have a stronger sense of responsibility over the outcome, than when they are passively attesting it, but not of authorship.

As to our second hypothesis, participants reported a higher SoA in the Full Predictability condition than in the Medium or Low Predictability conditions. This was not the case comparing the Medium Predictability and the Low Predictability conditions – which was not predicted by our hypothesis. This could suggest that SoA depends on an all or none evaluation regarding the predictability between an action and a consequence. However, it could also be that the difference of predictability was not perceived by the participants, as we did not inform them of the differences. This could suggest that implicit change of predictability did not affect SoA. We could not support more an all or none hypothesis or the awareness of predictability hypothesis with our data. Our results corroborate previous studies on the role of predictability in the SoA (Ma et al., 2019; Saad et al., 2024; Schwarz et al., 2022),

Finally, regarding our third research question on the interplay between intentionality and perceived causality. Our results show that the reported SoA was higher in the Free condition than in the Instructed and the Passive conditions, even in the Medium and Low Predictability conditions. This suggest that control on what to do even in an unpredictable world seems to contribute more to the reported SoA than merely acting or being passive. This is in line with research emphasizing the decrease of SoA when we do not choose what to do, but only execute (Caspar et al., 2016; Milgram, 1974). We also observed the decrease of reported SoA comparing the Full Predictability condition with the Medium and Low Predictability condition, but only in the Free and Instructed condition, and not in the Passive condition. The absence of effect of predictability in the Passive condition suggests that prediction is not sufficient to enhance SoA, we must be, at least, be the author of the action. Interestingly, it has been suggested that we can have a SoA for actions produces by another agent (Roselli et al., 2025; Wegner et al., 2004; Wohlschläger et al., 2003), therefore it is possible that only perceiving an action performed by another agent would be enough to observe an effect of predictability on reported SoA.

Temporal Binding

Regarding the intentionality dimensions results on the TB, we observe no difference between the Free condition and both the Instructed and Passive conditions. We do observe a stronger TB in the Passive condition than in the Instructed condition. This pattern was not predicted by our hypothesis. Several studies found stronger TB when participants had the choice on what to do, compared to when they were instructed (Barlas, 2019; Barlas et al., 2017; Barlas & Obhi, 2013; Borhani et al., 2017; Caspar et al., 2016, 2020, 2022; Pan et al., 2024; Pech & Caspar, 2023). The absence of difference between the free and instructed conditions in our experiment might be due to the presence of too many conditions to contrast with (see below for further explanation). The greater TB in the Passive condition than in the Instructed condition, might be explain because the selection could be more surprising, leading participants to pay more attention, in the Passive condition than when they know which would be the selected word in the Instructed condition. It is also likely that this difference is not representative of anything else than noise sampling. The interval estimates are quite variable, and spurious effect could indeed arise.

As predicted by our second hypothesis, we observed a stronger TB in the Full Predictability condition compared to both the Medium and Low Predictability conditions. This suggests that being able to predict an outcome increase the TB and is in line with previous studies (Beck et al., 2017; Di Costa et al., 2018; Engbert & Wohlschläger, 2007; J. Moore & Haggard, 2008; J. W. Moore et al., 2009; but three studies reported no effect or in the opposite direction: Desantis et al., 2012; Haering & Kiesel, 2014; Majchrowicz & Wierzchoń, 2018). However, no difference was found comparing the Medium and Low Predictability conditions. This absence of difference might again be explained by the fact that that the difference of predictability was not perceived by the participants.

Regarding our research question on the interplay between intentionality and predictability of the outcome, we did not find any specific patterns. Interestingly, the difference between the Full Predictability condition and both the Medium and Low Predictability conditions were found across the three levels of intentionality, suggesting that this is not specific to performing the action. Altogether, our results suggests that the TB is more sensitive to the predictability of the outcome than to the intentional component of the action. The fact that we did not replicate previous effect contrasting the Instructed and Free conditions make us cautious in the interpretation of our results. The presence of too many conditions might weaken the possibility to find an effect for the TB. Using interval estimate procedure, the TB differences between two conditions range between 15ms (Pan et al., 2024) and 73ms (Engbert et al., 2008) and is generally around 30ms (Barlas, 2019; Barlas et al., 2017; Borhani et al., 2017; Caspar et al., 2016; Engbert et al., 2008; Kong et al., 2024; Pech et al., 2025; Siebertz & Jansen, 2022; Suzuki et al., 2019; Wiesing & Zimmermann, 2024). Adding layer of conditions might not produce larger difference, therefore, only the strongest effect remains in the final comparison (i.e., predictability of the outcome in our case). TB might be considered only contrasting fewer conditions. This could be tested in future studies first contrasting two conditions (e.g., Instructed and Free) in a participant, and then in another day contrasting two other conditions (e.g., Full Predictability and Low Predictability), and finally in another day contrasting the four conditions. The order of the contrasts can be randomized to avoid an effect of days. If our reasoning is true, finding the two effect (i.e., intentionality and predictability) would be less likely when contrasting the four conditions than when contrasting the two conditions solely.

Readiness Potential

We observed that the RP was composed of a first negative shift until -0.5s, and a second positive shift between -0.5s and 0s (onset of the keypress). While we did not predict this pattern, as generally the RP is solely considered as a negative shift, some studies have discussed the potential dual stage of the RP, the early RP and the late RP (Jahanshahi et al., 1995; Jankelowitz & Colebatch, 2002; Kornhuber & Deecke, 2016; Neafsey, 2021; Schurger et al., 2021; Shibasaki & Hallett, 2006). The late RP is described as the last part before the movement onset, and there is a general agreement as to describe it as a marker of motor preparation. The early RP is described as the activity preceding the late RP and has been more debated as to whether reflecting a marker of an unconscious decision to act (Haggard, 2019; Libet et al., 1983), or an artefact of stochastic accumulation of noise (Schurger et al., 2012, 2021), or as an increase in likelihood to initiate an action aligned with the negative fluctuations of slow cortical potentials (Jo et al., 2014; Schmidt et al., 2016). The debate on the possibility of a dual stage of the RP, and of the characteristic of the early RP, is beyond the scope of this study.

However, we found some studies that discussed the possibility of positive RP. In a preprint Trov ò and colleagues (Trovò et al., 2021) found that 45% of their participants had a positive RP, and report that Freude and colleagues (Freude et al., 1988) observed 44% of positive RP at the trial level (however, we couldn't verify this information as we did not have access to this article). Moreover, VaezMousavi and Barry (VaezMousavi & Barry, 1993) also mention the results of Freude and colleagues, and replicate this finding were they observed 41% and 54% of positive RP, in two experiments respectively. The authors explain the augmentation in percentage of positive RP in the second experiment due to a split of attention. Finally, several studies led by Jo

(Jo et al., 2013, 2014, 2015), analysed the proportion of positive RPs prior to self-initiated actions, and found between 33% and 39% of positive RPs. Interestingly, they observed that this proportion of positive RPs increase when participants were instructed to introspect on their 'inner feeling' (Jo et al., 2015), or to withhold their intention (Jo et al., 2014). Altogether, it seems that task demands, and attention, play a role in the proportion of positive RPs. This could align with our observation, as the slope of the late part of the RP was more positive in the Free condition, where participant had to decide both what to do, and when to do it, compared to the Instructed condition when participant only decided when to act. Future studies are needed to clarify this phenomenon.

In line with our first hypothesis, we found a stronger RP in both the Free and Instructed condition than in the Passive condition. In the Passive condition, the RP slope estimated interval largely overlapped 0, suggesting that no RP was present, which is expected as no movement were performed. Contrarily to our hypothesis, we observed evidence that the RP – both early and late parts – were more negative in the Instructed condition than in the Free condition. Interestingly, this difference was not present when looking at the Free and Instructed condition in the Full Predictability condition. This suggest that when the outcome is predictable, the RP is not different when choosing what to do and when to act, rather than only choosing when to act. More specifically, this was due to a stronger RP when the outcome is predictable in the Free condition compared to when it was less predictable (i.e., Medium and Low Predictability conditions). This suggests that there is less preparation to act – as reflected by the RP – when we are not in control of the outcome anymore. Previous studies have shown that paying attention to our intention and movement lead to an increase of the RP (Jo et al., 2015; Verbaarschot et al., 2016). It could be that in the Free condition, when the outcome was not fully predictable, participants were paying less attention to what they were performing, compared to when they were in control, as well as when they were instructed in what to do.

Conclusion

There are some limitations in this study, first, we did not instruct the participants of the difference between the Full, Medium and Low Predictability conditions. This could explain why we did not observe difference between the Medium and Low Predictability conditions, as they could have been perceived similarly. Future studies might inform the participants of this to investigate if degree of predictability affect the markers of volition. Moreover, our Passive condition makes the selection unpredictable, as participants could not know in advance what would it be. Future studies could for instance use a Passive condition where the word that would be selected is already highlighted to avoid this effect. This would make the Instructed and Passive condition more similar. Finally, the interaction between intentionality and predictability was largely exploratory, without specific hypotheses. Replications are therefore crucial to confirm the observed results.

In this study, we investigate the effect of intentionality and predictability of the outcome on the markers of volition. We observed that both intentionality and predictability influenced the reported SoA, but the most important factor was to be the author of both the choice and the action (i.e., Free condition). Interestingly, the effect of predictability vanishes when we don't choose what to do (i.e., Instructed condition), nor when to do it (i.e., Passive condition). For the TB, we bring more evidence on the role of predictability in enhancing this effect. However, the effect of intentionality was not replicated. This might be explained by a stronger effect of predictability that reduce the likelihood to observe other effects. Finally, we observed a greater RP in the instructed condition than in the free condition. But this was only the case when the predictability of the outcome was reduced. This corroborates the role of goal representation in the motor preparation. When no clear goal could be prepared, in an unpredictable environment, choosing what to do could lead to weaker goal representation than following an instruction. Altogether, our study provides evidence that self-reported SoA is mainly driven by choosing what we do, TB depends more on predicting what will happens, and RP largely depends on what we aim at.

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