Title:

Action-effect prediction in volitional and stimulus-driven movement: Investigating sensory attenuation and misprediction sensitivity

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Abstract:

While volitional movement is thought to be initiated based on its anticipated capacity to achieve sensory goals, stimulus-driven movement may be generated with less regard for its specific effects. Sensorimotor processes that make use of action-effect predictions may therefore differ between these forms of movement, including sensory attenuation and the detection of mispredicted motor effects. In this study, we explored sensory attenuation by comparing the evoked response of externally-generated tones with those produced by participants (N = 61), both according to their own timing (i.e., volitionally) and in response to simple visual cues (i.e., stimulus-driven). The influence of stimulus identity prediction (i.e., the predictability of tone frequency) on N1 amplitudes was not found to differ between self- and externally-generated stimuli, or on the basis of volitional control. Reduced P2 amplitudes were observed in response to self-generated tones, which may suggest that these were subject to higher levels of attentional control, including processes involved in the termination of attention. To explore misprediction sensitivity, we compared the influence of stimulus identity prediction on N2b component amplitudes. A significant interaction was found to reflect heightened sensitivity to mispredicted outcomes of volitional action, compared with those of stimulus-driven movement. In light of recent evidence that attentional suppression may attenuate the primary cortical response to outcomes of stimulus-driven movement, we propose that this mechanism might also serve to diminish misprediction sensitivity. As such, these effects may represent important features of sensorimotor processing that assist in differentiating stimuli on the basis of self-generation and intentionality.

Keywords:

Sensory Attenuation; Internal Forward Models; Prediction; Misprediction Sensitivity; Attention.

1. Introduction

Self-generated stimuli have been found to be subjectively less intense and elicit smaller neurophysiological responses than identical stimuli that are produced externally (e.g., Blakemore et al., 1998; Schafer & Marcus, 1973). This ‘sensory attenuation’ phenomenon is believed to reflect the suppression of stimuli based on one’s predictions regarding the outcomes of movement (Wolpert, 1997). In particular, the internal forward model of motor control (IFM; Miall & Wolpert, 1996; Wolpert et al., 1995) proposes that duplicates of motor commands (i.e. 'efference copies'; von Holst & Mittelstaedt, 1950) are transmitted to sensory cortices and activate representations of the anticipated consequences to movement (i.e., 'corollary discharge'; Sperry, 1950). Information arriving through afferent channels are believed to be compared with these predictions, facilitating the suppression of sensations that are anticipated on the basis of motor commands (Miall & Wolpert, 1996; Wolpert et al., 1995). This mechanism is believed to also give rise to one’s sense of agency over self-generated stimuli, which is thought to reflect the degree to which the outcomes of movement correspond to those that are predicted (and therefore intended) based on motor commands (see Haggard, 2008). In this way, sensory attenuation is thought to correspond to one’s perception of agency in the production of stimuli.

Since its inception in the literature, sensory attenuation has commonly been explored through examination of the N1 component of the evoked potential (see Schafer & Marcus, 1973). Research has demonstrated reduced N1 amplitudes in response to self-generated visual and auditory events compared with identical stimuli that are externally-generated (e.g., Aliu et al., 2009; Baess et al., 2011; Baess et al., 2008; Bednark et al., 2015; Cao et al., 2017; Ford et al., 2014; Lange, 2011; Sanmiguel et al., 2013; Schafer & Marcus, 1973; Sowman et al., 2012; Timm et al., 2016). The auditory N1 has several neural generators, including within the supratemporal plane and superior temporal gyrus, as well as the motor cortex and/or cingulate gyrus (Giard et al., 1994; Näätänen & Picton, 1987; Zouridakis et al., 1998). As the auditory N1 reflects activity within the somatosensory cortex and is sensitive to change in stimulus intensity (Mulert et al., 2005), its reduced amplitude in response to self-generated sound has long been attributed to the operation of motor-based predictions within the IFM (e.g., Baess et al., 2008; Timm et al., 2014).

Despite a wealth of research exploring the phenomenon of sensory attenuation, research has yielded discrepant findings with respect to the role of action-effect prediction (i.e., the degree to which the identity of resulting stimuli, such as a tone's frequency, may be predicted based on a specific motor action). While some research has identified a positive association between action-effect predictability and sensory attenuation (Baess et al., 2008; Darriba et al., 2021), others have not found a significant relationship (Bednark et al., 2015; Dogge, Hofman, et al., 2019; Harrison et al., 2023; Le Bars et al., 2019). In some cases, action-effect predictability has been associated with an *increase* in one's perceptual sensitivity to self-generated stimuli (Dogge, Custers, et al., 2019; Guo & Song, 2019; Reznik et al., 2015; Reznik et al., 2014; Thomas et al., 2022; Yon et al., 2021) and accompanying neurophysiological activity (Reznik et al., 2021; Reznik et al., 2014; Yon et al., 2018). These findings highlight the need for further research into the role of action-effect prediction in the sensory attenuation phenomenon.

Several methodological confounds have affected research into sensory attenuation. Firstly, much of the research that has explored sensory attenuation of the N1 has involved comparison of self- and externally-generated stimuli that differ in terms of their temporal predictability (Hughes et al., 2013). This research has typically compared self-generated stimuli that are produced immediately in response to movement with externally-generated stimuli that are not predictable in time. As temporal predictability has been associated with reduced N1 amplitudes (e.g., Lange, 2009; Weiskrantz et al., 1971), such differences may confound the effects observed in these experiments. Indeed, research that has compared N1 components resulting from self-generated stimuli with those of externally-generated events that are predictable in time has found that sensory attenuation is reduced (Harrison et al., 2021; Sowman et al., 2012), absent (Egan et al., 2023) or potentially even reversed (Kaiser & Schütz-Bosbach, 2018). These findings highlight the importance of understanding and accounting for the effects of temporal predictability in studies of sensory attenuation.

Differences in attention and physiological arousal have also been highlighted as potential confounds in sensory attenuation research (see Horváth, 2015; Hughes et al., 2013). These potential effects may be evidenced by reduced P2 amplitudes to self- versus externally-generated stimuli (e.g., Bolt & Loehr, 2021, 2023; Harrison et al., 2021), as a reduction in the amplitude of this component has been associated with higher levels of attention (García-Larrea et al., 1992; Hillyard et al., 1973; Näätänen et al., 1978; Novak et al., 1992) and physiological arousal (e.g., Colrain et al., 2000). Attention-related P2 effects include the well-documented ‘processing negativity’, whereby higher levels of attention to a task-relevant stimulus produces simultaneous enhancement of its resulting N1 amplitude and reduction in P2 amplitudes (Hillyard et al., 1973; Näätänen et al., 1978). While consistent with evidence demonstrating reduced P2 amplitudes to self-generated stimuli, heightened attention is not able to account for the simultaneous *suppression* of N1 amplitudes. Similarly, higher states of arousal have been found to *increase* N1 amplitudes (Huang et al., 2017), meaning that such differences are unlikely to account for the attenuation of this component.

Significantly, attention-related suppression of the P2 has been observed independently of the N1 in a manner that reflects both task-relevance and the withdrawal of attention from non-target stimuli. In particular, research has demonstrated reduced P2 amplitudes for non-target stimuli in auditory oddball tasks when compared with those elicited by identical stimuli that are not task-relevant (García-Larrea et al., 1992; Novak et al., 1992). These findings have led to the suggestion that reduced P2 amplitudes reflect enhanced attentional control during auditory discrimination tasks, including processes involved in the *termination* of selective attention (Crowley & Colrain, 2004; García-Larrea et al., 1992). A reduction in P2 amplitudes to self- versus externally-generated stimuli, which has been robustly observed in research that has accounted for the effects of temporal predictability (e.g., Bolt & Loehr, 2021, 2023; Harrison et al., 2021), may therefore reflect heightened attentional control.

While representing a potential confound to the conclusions of prior research, attentional differences may also contribute to mechanisms that serve to distinguish different types of self-generated events. In particular, Harrison et al. (2023) observed apparent Pd activity that coincided with the auditory N1 components elicited by self-generated stimuli and corresponded to a reduction in their amplitudes. The Pd, which is believed to reflect active suppression of spatially-oriented attention, manifests as relative positivity over parieto-occipital regions contralateral to distractor stimuli (Sawaki et al., 2012; Sawaki & Luck, 2013). This activity, which Harrison et al. (2023) observed contralateral to effector muscles and describe in the context of motor action as the ‘lateralised post-enactment potential’, was larger following movement that was temporally-cued relative to uncued movement. Findings from Harrison et al. (2023) may therefore reflect cross-modal suppression of attention to certain forms of self-generated stimuli, which contributes to an attenuation of resulting N1 amplitudes.

To understand attentional effects on the processing of self-generated stimuli, it is informative to consider differences in the use of action-effect prediction between volitional and stimulus-driven movement. Brass and Haggard (2008) identified that intentional movement (i.e., action that is described in the present investigation at ‘volitional’) involves control over what, when and/or whether to act. In contrast, these aspects of control are contingent on observed (i.e., external) stimuli when movement is *stimulus-driven*. While intentional movement is believed to be generated on the basis of action-effect predictions (i.e., selection of a motor action based on its intended effects), stimulus-driven movement may instead rely on stimulus-response associations (i.e., movement in reaction to an external stimulus; Herwig et al., 2007; Neumann, 1984). In this manner, volitional movement is guided by its anticipated sensory consequences (Herwig et al., 2007; Pfister et al., 2011) while stimulus-driven movement may operate as a form of prepared reflex with less regard for its specific effects (see Hommel, 2000).

In accordance with distinct sensorimotor mechanisms, research has demonstrated differences in the neurophysiological response to mispredicted outcomes of intentional and stimulus-driven movement (Le Bars et al., 2019). Specifically, Le Bars et al. (2019) observed larger N2b amplitudes in response to deviant stimuli (i.e., compared to standard stimuli) in an oddball task when participants chose *what* motor activity to undertake. In contrast, Le Bars et al. (2019) found that this effect was absent for self-generated stimuli when the nature of participants' eliciting movement was determined by external cues. Significantly, larger N2b amplitudes have been attributed to the perception of error in relation to movement outcomes (see Ferdinand et al., 2008; Folstein & Van Petten, 2008). As noted by Le Bars et al. (2019), this finding suggests that an agent is more sensitive to movement errors (i.e., show increased misprediction sensitivity) when they have chosen *what* action to undertake.

Several questions are raised in association with the reviewed literature. Firstly, discrepancies in previous findings warrant investigation into the role of action-effect predictability in sensory attenuation of the auditory N1. Given that identity prediction of externally-generated stimuli has also been associated with reduced N1 amplitudes (e.g., Lange, 2009), it is necessary that the effects of *action-effect* predictability are compared with those of overall stimulus identity prediction. Through investigation of differences in P2 component amplitudes, the potential role of differences in attentional control may be further explored in the context of these effects also. Secondly, research has demonstrated differences in misprediction sensitivity (i.e., as reflected by differences in N2b amplitudes to predicted and unpredicted stimuli) based on whether participants have chosen *what* action to undertake (Le Bars et al., 2019). In contrast, effects involving attentional suppression on early cortical activation (i.e., N1 amplitudes) have been associated with whether participants have chosen *when* to act (Harrison et al., 2023; Harrison et al., 2021). Research is therefore needed to explore whether these effects represent the same underlying distinction (i.e., between volitional and stimulus-driven movement) or may be attributable to different mechanisms.

The present study therefore aimed to explore the influence of stimulus identity prediction on neurophysiological responses to self- and externally-generated stimuli. We sought to differentiate sensorimotor processes in stimulus-driven and volitional action, and to assess and control for the effect of temporal predictability. These aims were achieved through comparison of the N1, P2 and N2b components of event-related potentials (ERPs) elicited by self- and externally-generated sound that differed with respect to these factors. Self-generated tones were produced according to participants' own timing (i.e., volitionally) or in response to simple visual cues (i.e., stimulus-driven). Based on recent findings (Harrison et al., 2023; Harrison et al., 2021), it was hypothesised that tones produced by cued movement would elicit reduced N1 and enhanced P2 amplitudes. The effects of temporal predictability were explored through examination of differences associated with the presence or absence of visual cues to indicate the onset of externally-generated tones. In accordance with prior research (e.g., Harrison et al., 2021; Lange, 2009; Weiskrantz et al., 1971), it was hypothesised that N1 amplitudes would be reduced when the onset of externally-generated tones was made predictable. To assess effects relating to stimulus identity prediction, two variants of each condition were presented in blocks of either a single tone type or with two different frequencies. While the tone frequency of each trial was predictable in the single-tone variant (i.e., 100% predictability), trials in the intermixed two-tone variant involved the presentation of a tone frequency with 50% predictability. It was hypothesised that the 100% conditions would be associated with smaller N1 amplitudes compared with those in the 50% conditions.

Given mixed findings in previous research, specific hypotheses were not made with respect to the effects of action-effect predictability on N1 amplitudes (i.e., comparing the effects of stimulus identity prediction in self- and externally-generated conditions). However, an interaction was hypothesised between action-effect predictability and volition (i.e., contrasting cued and uncued movement) on N2b component amplitudes. Specifically, it was anticipated that 50% conditions would be associated with larger N2b amplitudes than 100% conditions and that this effect would be greater for tones resulting from uncued movement compared with cued movement. This finding would reflect differences in misprediction sensitivity based on volitional control over *when* movement is enacted, in a similar manner to effects demonstrated by Le Bars et al. (2019) relating to control over *what* action is produced.

2. Materials and Methods

2.1. Participants

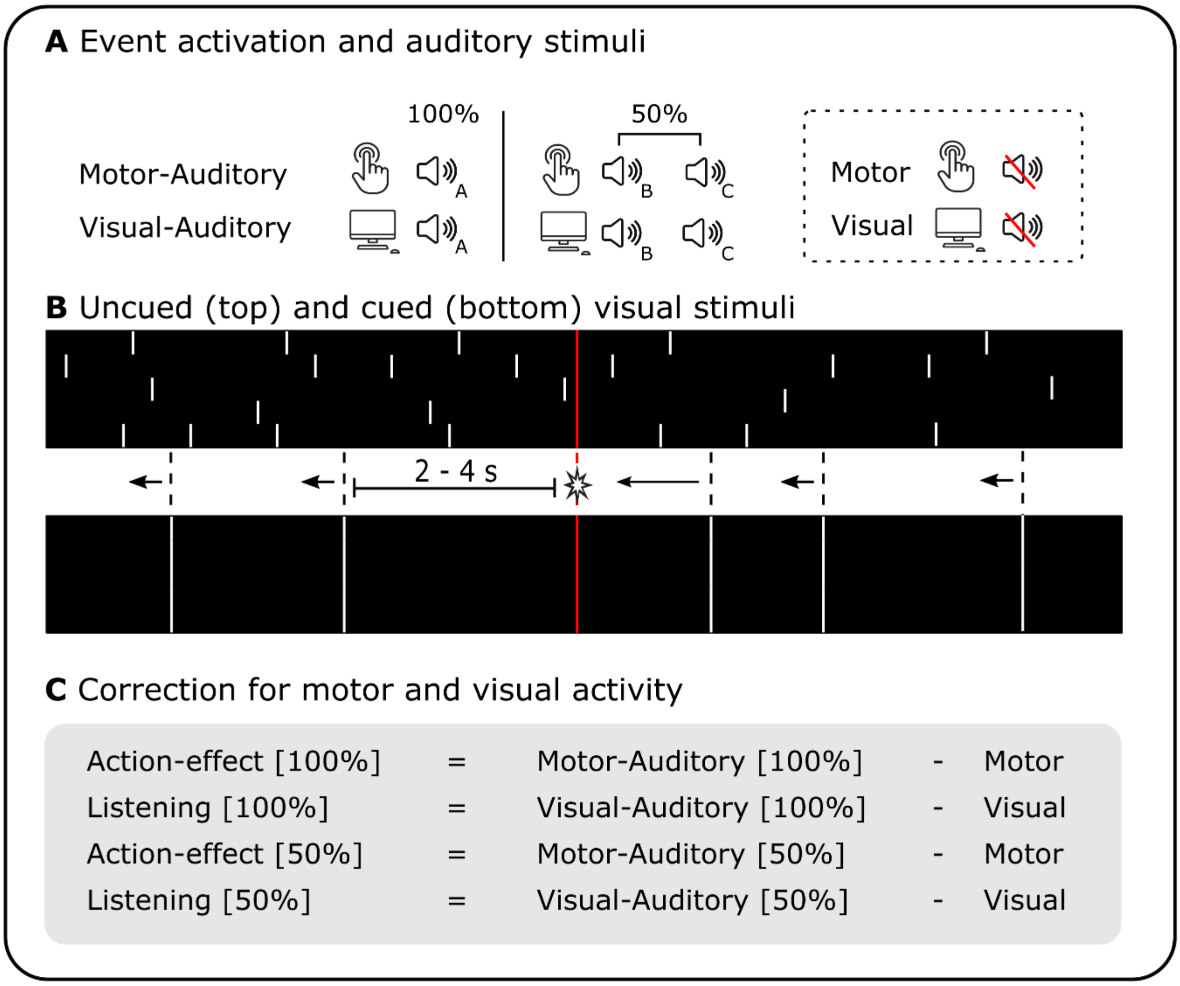
Sixty-one healthy participants (42 females), aged between 18 and 50 years (*M* = 22.07, *Mdn* = 20.27, *SD* = 5.81), volunteered in exchange for credit towards an undergraduate psychology unit at the University of New South Wales (UNSW). All participants reported normal or corrected-to-normal vision, and normal hearing. Potential exclusion criteria included recent recreational substance use (i.e., <48 hours), and self-reported diagnoses of psychotic or neurological disorder. No exclusions were necessary on these bases. The sample size was constrained by participant and experimenter availability during the academic term and was comparable to those obtained in similar recent investigations (Harrison et al., 2023;

Harrison et al., 2021). The study was approved by the UNSW Human Research Ethic Advisory Panel and written informed consent was obtained from participants prior to their involvement.

2.2. Design

Participants were seated facing a BenQ XL2420T computer monitor (24-inch, 1920 × 1080 resolution screen) at a distance of approximately 60 cm. They were fitted with an EEG recording cap, which was equipped with a BioSemi ActiveTwo system containing 64 Ag/Cl active electrodes. These electrodes were positioned according to the extended 10:20 layout (see Böcker et al., 1994). Each participant was also fitted with electrodes below the left eye, on their nose, adjacent to the outer canthus of each eye, and on their left and right mastoids. Participants wore Sennheiser HD201 headphones, placed over the recording cap and electrodes. Grounding was provided by the CMS and DRL cap electrodes while data acquisition was undertaken with a sampling rate of 2048 Hz. In each condition, participants were asked to fix their gaze on a vertical red (fixation) line at the centre of the screen. This line was one pixel wide and approximately six centimetres long (i.e., corresponding to a visual angle of approximately 5.4°).

Fig. 1: Protocol schematic and visual stimuli



Action-effect [100%] = Motor-Auditory [100%] - Motor
Listening [100%] = Visual-Auditory [100%] - Visual
Action-effect [50%] = Motor-Auditory [50%] - Motor
Listening [50%] = Visual-Auditory [50%] - Visual

A. In *motor-auditory* and *motor* conditions, participants pressed a keyboard button to initiate events. These were initiated externally, by the computer, in the *visual-auditory* and *visual* conditions. Events involved presentation of a tone via participant headphones in the *motor-auditory* and *visual-auditory* conditions, while silent audio tracks were used to mark events in the *motor* and *visual* conditions. In *100%* variants of the *motor-auditory* and *visual-auditory* conditions, all tones were of a single frequency. A balanced and randomised sequence of two different tone frequencies was presented in the *50%* variants (i.e., one of two different tones was presented in each trial). Conditions were presented in separate blocks, each containing 70 trials. **B.** Schematic demonstrating stimulus presentation during *uncued* blocks (top) and *cued* blocks (bottom). In *uncued* blocks, vertical line fragments were randomly distributed across five adjacent rows and moved leftwards across the screen. In the *uncued motor-auditory* and *uncued motor* conditions, participants were instructed to ignore these lines, keep their eyes fixed on a red fixation line and press a keyboard button once every two to four seconds approximately. The timing of events in the preceding *uncued motor-auditory* or *uncued motor* condition provided the basis for timing in other conditions. In *cued* conditions, the timing of events was indicated by long white lines that moved from right to left across the screen. In the *cued motor-auditory* and *cued motor* conditions, participants were instructed to press the keyboard button to initiate events at the precise moment that each line intersected with the fixation line. Events were externally triggered according to the same timing in *visual-auditory* and *visual* conditions, while participants listened passively with their eyes fixed on the red fixation line. The timing of these events was not predictable to participants in the *uncued visual-auditory* and *uncued visual* conditions, while the long white lines indicated their timing in the *cued* variant of each. **C.** *Motor-auditory* conditions (i.e., 100% and 50% variants) were corrected for motor (and visual) activity by subtracting the equivalent *motor* condition (i.e., *uncued* and *cued*). Similarly, visual activity was removed from the *visual-auditory* conditions by subtracting the equivalent *visual* condition. Motor-corrected motor-auditory conditions are henceforth described as *action-effect,* while visual-corrected visual-auditory conditions are described as *listening.* These conditions also differed on the basis of whether they were cued or uncued, resulting in a total of eight analysis conditions.

2.2.1. Uncued conditions

In *uncued* conditions, a sequence of randomly-spaced white line fragments were presented across five adjacent rows that collectively spanned the height of the fixation line (see Fig. 1B top panel). The line fragments appeared on the right of the screen and moved leftward at a pace of approximately 3°/s. In the *motor-auditory* and *motor* variants of the *uncued* condition, participants were instructed to press a keyboard button repeatedly. They were asked to make the timing of their button presses unpredictable to an observer, and to aim for approximately two to four seconds between each press. Participants were specifically instructed not to deliberately synchronise their button press to passing line fragments or avoid doing so. If participants pressed within two seconds of the preceding trial, the event was not activated and a reminder to “slow down” was displayed above the fixation line from 400 ms to 800 ms after the button-press.

In the *uncued motor-auditory* condition, each button press resulted in delivery of a pure tone (85 dB, SPL/A-weighted, 10 ms ramp, 100 ms duration) via participant headphones (see Fig. 1A). In the *100%* variant of this condition, all tones were of the same frequency. These could be either *low*, *medium* or *high* pitch tones, corresponding to 500 Hz, 1000 Hz and 1500 Hz respectively. Each button press elicited one of two equiprobable tones in the *50%* variant, with the total number of each tone type balanced within blocks and presented in randomised order. Allocation of the three tone frequencies to the *100%* and *50%* variants was counterbalanced across participants. Three tone frequencies were used to ensure that different tones were presented in the 50% and 100% conditions, thereby minimising the degree to which expectations were influenced by the contingency of tones in prior blocks. In the *motor* variant of the *uncued* condition, silent audio tracks were triggered to mark each button press. The latency of audio track delivery (i.e., both tones and silent tracks) was reduced through use of an AudioFile Stimulus Processor (Cambridge Research Systems). The inaudible (silent) audio tracks were included to mark events in the EEG data with an identical latency to conditions that involved audible stimuli.

Participants observed passively in the *visual-auditory* and *visual* variants of the *uncued* condition. The auditory stimuli (i.e., 100% and 50%) were the same as those used in the *uncued motor-auditory* blocks. The allocation of tone frequencies to each condition, and their order within *50%* blocks, was also the same as for the *uncued motor-auditory* conditions. The timing of their presentation was matched to the timing of participants' button presses in the most recent *uncued motor-auditory* or *uncued motor* condition. In *visual* conditions, the timing of silent audio tracks was determined on this basis as well.

2.2.2. Cued conditions

In *cued* conditions, vertical white (stimulus) lines appeared on the right of the screen and moved leftward at a constant rate of approximately 3°/s. Specifically, this corresponded to a period of 16 seconds between their appearance at the edge of the screen and arrival at the central point of fixation. These lines were one pixel wide and approximately six centimetres long (i.e., equal dimensions to the fixation line; see Fig. 1B bottom panel). In the *motor-auditory* and *motor* variants of the *cued* condition, participants were instructed to press the keyboard button at the precise moment that each stimulus line intersected with the fixation line. The spacing of the lines, and therefore the timing of events, was based on the spacing of participants' button presses in the preceding *uncued motor-auditory* or *uncued motor* block (i.e., the most recently presented). Button presses in the *cued motor-auditory* condition elicited the same auditory stimuli as described for the *uncued motor-auditory* and *uncued visual-auditory* conditions. That is, different blocks presented either a single tone type (i.e., *100%* variant) or one of two different frequencies (i.e., *50%* variant) in each given trial.

Button presses again triggered delivery of a silent audio track to mark events in the *cued motor* condition.

Participants were instructed to passively observe in the *cued visual-auditory* and *cued visual* conditions. In the *cued visual-auditory* condition, tones were presented at the precise moment that each stimulus line intersected with the fixation line. Auditory stimuli were the same as those described for other conditions, with *100%* and *50%* block varieties. Silent audio tracks were used to mark these events in the *cued visual* condition.

2.2.3. Block presentation

Participants completed a single block of each of the twelve experimental conditions. Each block involved a total of 70 trials and took approximately 3 minutes to complete. The experiment lasted approximately 2 hours, including 30 minutes to set-up, 1 hour for testing, and 30 minutes for clean-up. The testing time incorporated a 15-minute break at the half-way point. Block order was pseudorandomised, such that the *uncued motor-auditory* (i.e., 100% and 50% variants) and *uncued motor* conditions were presented in the first, fifth and ninth block. The allocation of these conditions to each block was counterbalanced across participants, while the order of the nine remaining conditions was randomised for each.

2.3. EEG Processing

EEG data were referenced to the nose electrode and processed offline in BrainVision Analyser (Version 2.2.0; Brain Products GmbH, Gilching, Germany). A 50-Hz notch filter and 0.1 Hz to 30 Hz zero phase-shift Butterworth band-pass filter (half-amplitude, high-pass 12 dB/Oct and low-pass 48 dB/Oct slopes) were applied. Trials were segmented into 600 ms epochs, commencing 200 ms prior to each event. Recordings from the electrodes below participants' left eyes were used in conjunction with those at Fp1 to produce vertical electro-oculograms (EOGs). Horizontal EOGs were constructed based on recordings at the electrodes that were placed adjacent to the outer canthus of each eye. EOGs were then used to correct eye-movement artefacts using the method described by Miller et al. (1988), which is an extension to the approach by Gratton et al. (1983). This method uses a standardised regression to identify the relationship between EOG and EEG data, allowing estimation and removal of activity associated with eye-movement from the EEG signal at each timepoint (see Miller et al., 1988). Baseline correction was applied using average recordings in the 200 ms prior to each event. This involved subtraction of the average voltage between -200 ms and 0 ms from every datapoint in the waveform.

In accordance with Harrison et al. (2021), epochs that were found to contain peak-to-peak amplitudes in excess of 200 µV were then excluded. This resulted in very similar rates of artefact rejection, and therefore numbers of retained trials, across the different conditions (see Table A4). Of the 70 trials presented for each condition, a similar number of trials were retained for the *motor*/*motor-auditory* and *visual*/*visual-auditory* conditions (*M* = 67.48 and *M* = 67.87, respectively). Trials in which participants pressed within 2 seconds of the preceding trial, and were reminded to slow down, did not activate events and therefore did not contribute to the results. These reminders were infrequently needed and consistent across variants of the *uncued* self-generation conditions, including the *50%* variant (*M* = 0.82, *SD* = 1.31), *100%* variant (*M* = 0.74, *SD* = 1.14), and *motor* variant (*M* = 0.66, *SD* = 1.05). Averaged waveforms were developed, by condition and participant, based on the remaining epochs. Activity associated with the auditory stimuli in *motor-auditory* and *visual-auditory* conditions was isolated by subtracting equivalent *motor* and *visual* waveforms (see Fig. 1C). These analysis conditions represented *100%* and *50%* varieties of each task level (i.e., *uncued action-effect, cued action-effect, uncued listening* and *cued listening*).

Consistent with previous analyses (e.g., Harrison et al., 2021), the N1 and N2b were analysed based on pooled recordings at Fz, FCz and Cz, while the P2 was analysed based on pooled recordings at FCz, Cz and CPz. Peak latencies of the N1 and P2 components were identified using the collapsed localiser method (see Luck & Gaspelin, 2017). This involved identifying component latencies within a collapsed waveform that represented the average voltages across all participants and conditions. When defined as the most negative local minimum between 50 ms and 150 ms, the N1 was found to have occurred 90.3 ms post-stimulus. The P2 was found to have occurred 161.1 ms after stimulus onset, when defined as the most positive local maximum between 40 ms and 170 ms post-stimulus. While this peak detection range was earlier than in some other studies of the P2 (e.g., Crowley & Colrain, 2004), it was selected based on visual inspection of the grand average waveforms and to minimise influence associated with effects involving the N2b component. Importantly, peak latencies for both the N1 and P2 components were comparable with those observed in other similar studies (e.g., Harrison et al., 2023; Harrison et al., 2021). Because a clear N2b component was only evident in the *50% uncued action-effect* condition, the grand-averaged waveform of this condition was used as the basis for determining its latency. This decision was made post hoc, based on visual inspection of the grand average waveforms. When taken as the most negative local minimum between 150 ms and 300 ms post-stimulus, the N2b peak was found to have occurred 200.7 ms post-stimulus. This was similar to the N2b latency observed in other comparable studies (e.g., Le Bars et al., 2019; Ferdinand et al., 2008).

Visual inspection of the waveforms revealed an apparent P3 component in the *50% uncued action-effect* condition. Post hoc analyses revealed that the P3 had a latency of 279.3 ms, when taken as the most positive local maximum between 250 ms and 350 ms. As research has indicated that the N2b is always accompanied by a P3 (Folstein & Van Petten, 2008; Pritchard et al., 1991), the presence or absence of this component has relevance to the interpretation of differences between conditions within the N2b range (i.e., whether these are attributable to N2b effects or other components). The apparent absence of a P3 component in other conditions provided further indication that these evoked responses also lacked N2b component activity. However, to explore any potential bias associated with the approach taken to N2b peak selection, a sensitivity analysis was conducted based on the same parameters (i.e., the most negative local minimum between 150 ms and 300 ms post-stimulus) within a grand average waveform containing all 50% conditions. When based on this method, the N2b component peak was found to have occurred marginally later (i.e., 203.1 ms compared with 200.7 ms post-stimulus).

2.4. ERP Analyses

Statistical analyses were based on average recordings, by condition and participant, within 20 ms windows that were centred on each component's peak. This was consistent with the approach taken in recent studies that have involved a similar design (e.g., Harrison et al., 2023; Harrison et al., 2021). Analyses of the N1 involved average recordings between 80 ms and 100 ms post-stimulus, while the P2 was analysed based on those between 151 ms and 171 ms post-stimulus. The N2b analysis window was between 191 ms and 211 ms post-stimulus. Descriptive statistics of the component amplitudes for each condition are provided in Table A1.

Three 2 x 4 repeated measures ANOVAs were used to investigate the main effects of *stimulus identity prediction* (i.e., *100%* versus *50%*) and *task*, as well as their interaction, on N1, P2 and N2b amplitudes respectively. Results from these ANOVAs are provided in Table A2. The four *task* conditions were included in a single factor on the basis that, although *cued* and *uncued* variants of both self- and externally-generated stimuli were present, changes in the level of one factor did not equate to the same conceptual change between levels in the other. For example, cueing stimuli in the *visual-auditory* conditions contributed to temporal predictability while those in the *motor-auditory* conditions did not (i.e., stimuli in both *uncued motor-auditory* and *cued motor-auditory* conditions were predictable in time). Orthogonal contrasts were constructed to partition variance within the ANOVA models and reduce Type I error inflation by facilitating independent linear comparison of the *task* conditions (i.e., *uncued action-effect, cued action-effect, uncued listening* and *cued listening).* These contrasts supported investigation of the effects of *volition* ([3, -1, -1, -1]), *cued self-generation* ([0, 2, -1, -1]) and *temporal prediction* ([0, 0, -1, 1]). While similar comparisons may have also been facilitated based on a different set of orthogonal contrasts, this specification prioritised examination of the *volition* effect given its overarching theoretical relevance in the present study. Based on the procedure described by Field et al. (2012), these were assessed using equivalent linear regressions with random intercepts that varied by participant among the *stimulus identity prediction* and *task* factors. Where non-sphericity was identified by Mauchly's tests (Mauchly, 1940), corrections were applied using the Greenhouse-Geisser method (Geisser & Greenhouse, 1958). Bayes factors (BF_{10}) were also produced for the omnibus repeated measures ANOVAs and planned comparisons. These included Cauchy priors with an r-scale of 1/√2 (see Morey & Rouder, 2018), as recommended across a range of Bayesian statistical procedures including point null hypothesis testing (Jeffreys, 1998) and regression (Gelman et al., 2008).

2.5. Inter-trial intervals

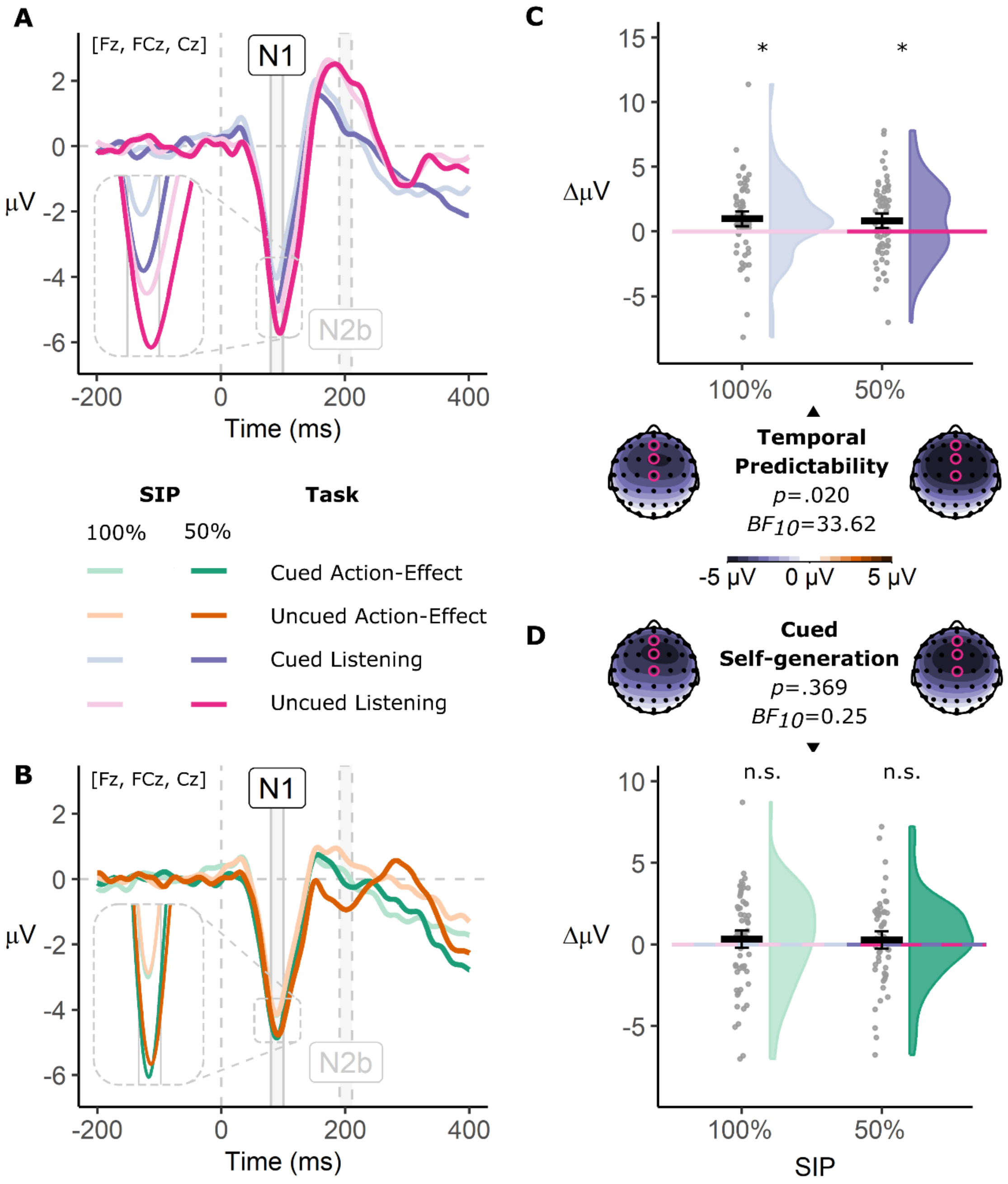
The consistency in inter-trial intervals (ITIs) was assessed across experimental conditions based on a 3 x 2 x 2 repeated measures ANOVA. The structure of this ANOVA differed from those used to investigate component amplitudes in the *analysis* conditions (i.e., following correction for *motor* and *visual* activity). In particular, potential differences were investigated based on the nature of *auditory stimuli* (i.e., *100%, 50%* or *silent*), *event activation* (i.e., *motor-* and *motor-auditory* versus *visual* and *visual-auditory*) and *visual stimuli* (i.e., *uncued* versus *cued*).

3. Results

3.1.1. N1

The ANOVA revealed statistically significant main effects of both *stimulus identity prediction*, $F(0.86, 51.72) = 11.86$, $p = .001$, $\eta_p^2 = 0.17$, $BF_{10} = 9.12$, and *task*, $F(2.94, 176.56) = 2.91$, $p = .036$, $\eta_p^2 = 0.05$, $BF_{10} = 0.81$ (see Fig. 2). The effect of stimulus identity prediction was such that N1 amplitudes were smaller in the *100%* conditions, compared with the *50%* conditions. Planned comparisons indicated a significant effect of *temporal prediction* (i.e., contrasting *cued listening* and *uncued listening),* $t(180) = 2.34$, $p = .020$, $d = 0.30$, $BF_{10} = 33.62$, such that *cued listening* exhibited a smaller (i.e., less negative) N1 amplitude than *uncued listening.* The effects of *volition* and *cued self-generation* were not found to be significant (see Table A3 for detail). Nor were interactions between the effect of *stimulus identity prediction* and each of the planned comparisons, including *volition*, $t(240) = -0.05$, $p = .964$, $d = -0.01$, $BF_{10} = 0.16$, *temporal prediction*, $t(240) = -0.32$, $p = .751$, $d = -0.04$, $BF_{10} = 0.11$, and *cued self-generation*, $t(240) = -0.13$, $p = .896$, $d = -0.02$, $BF_{10} = 0.17$. In each case, the associated Bayes factor indicated substantial evidence in favour of a null effect (see Jeffreys, 1998).

Fig. 2: Analyses of N1 component amplitudes



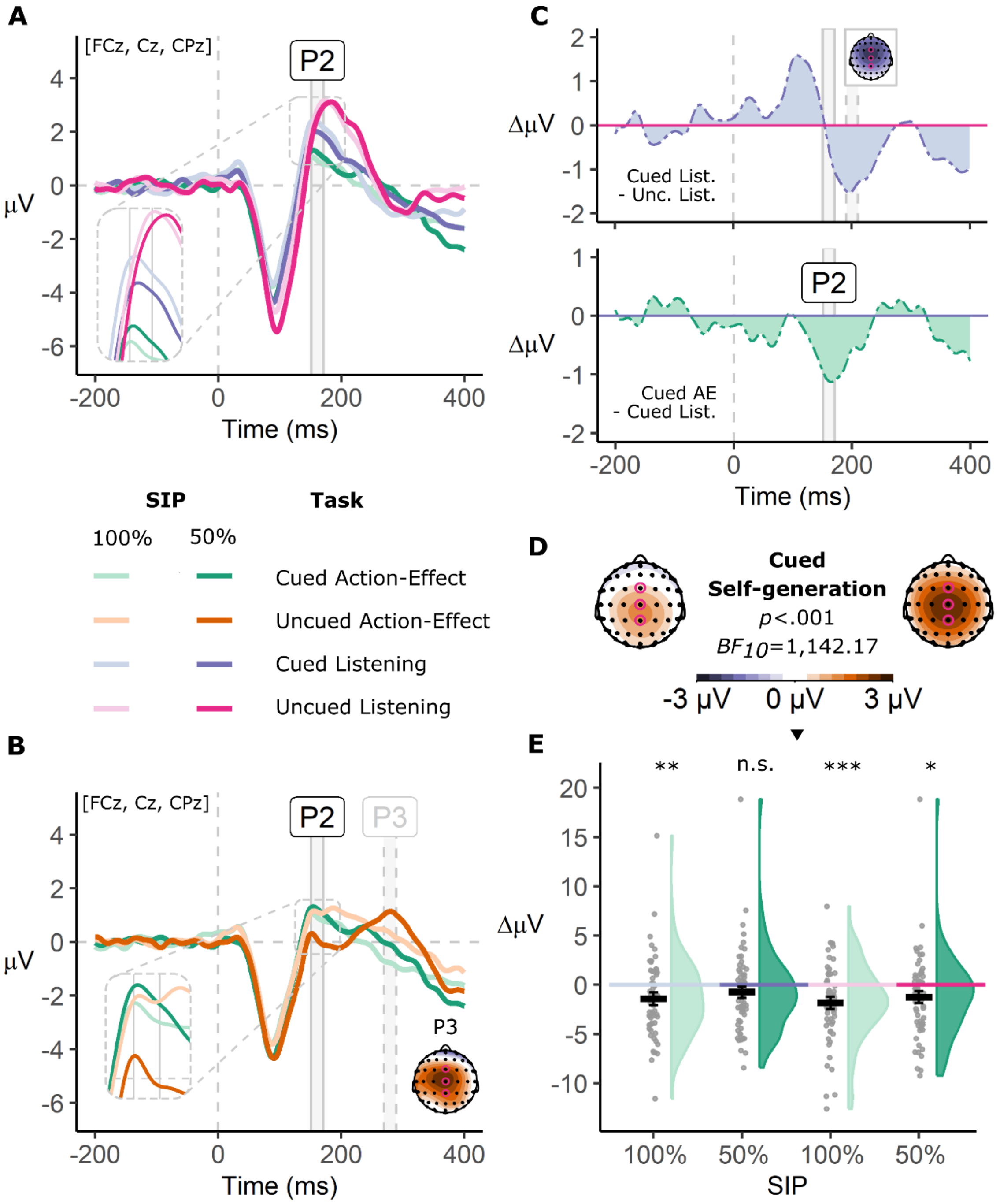
A-B. Pooled grand-averaged recordings at Fz, FCz and Cz, demonstrating mean amplitudes for the (A) *listening* conditions and (B) *action-effect* conditions, by *stimulus identity prediction* (SIP; i.e., *100%* and *50%*). Dotted rectangles mark the window representing N2b component analyses, which were based on the same pooled electrodes as the N1. **C.** The effect of *temporal predictability* on N1 amplitudes, including (top) within-subject differences in mean amplitudes between *cued listening* and *uncued listening* conditions by SIP, and (bottom) orthogonal contrast of *temporal prediction* with accompanying topographic maps demonstrating the *cued listening* (left) and *uncued listening* (right) conditions. Pink rings indicate analysis electrodes. **D.** The effect of *cued self-generation* on N1 amplitudes, including (bottom) within-subject differences in mean amplitudes between *cued action-effect* and the average of *cued listening* and *uncued listening* by SIP, and (top) the orthogonal contrast results. Pink rings indicate analysis electrodes. Error bars represent 95% confidence intervals.

Note. n.s. = not significant, * $p < .05$

3.1.2. P2

The ANOVA revealed a statistically significant effect of *task* on P2 amplitude, $F(2.22, 133.15) = 9.25$, $p < .001$, $\eta_p^2 = 0.13$, $BF_{10} = 1{,}952.55$ (see Fig. 3). In contrast, non-significant effects were observed with respect to *stimulus identity prediction*, $F(0.77, 45.95) = 1.67$, $p = .201$, $\eta_p^2 = 0.03$, $BF_{10} = 0.33$, and the interaction between *task* and *stimulus identity prediction*, $F(2.30, 137.84) = 1.97$, $p = .120$, $\eta_p^2 = 0.03$, $BF_{10} = 0.25$. Planned comparisons revealed statistically significant effects of both *cued self-generation*, $t(180) = -3.57$, $p < .001$, $d = -0.46$, $BF_{10} = 1{,}142.17$, and *volition*, $t(180) = -2.09$, $p = .038$, $d = -0.31$, $BF_{10} = 1{,}223.77$, on P2 amplitude. The *cued self-generation* effect indicated that P2 amplitudes were smaller in the *cued action-effect* condition than the *listening* conditions (i.e., *uncued listening* and *cued listening).* The nature of the *volition* effect was such that P2 amplitudes were smaller in the *uncued action-effect* condition, compared with mean P2 amplitudes across all other conditions. Other planned comparisons and interactions with *stimulus identity prediction*, were not found to be statistically significant (see Table A3).

Fig. 3: Analyses of P2 component amplitudes



A-B. Pooled grand-averaged recordings at FCz, Cz and CPz, demonstrating mean amplitudes for (A) *cued action-effect, cued listening* and *uncued listening* conditions and (B) *action-effect* conditions, by *stimulus identity prediction* (SIP; i.e., *100%* and *50%*). The dotted rectangle and accompanying topographic map in (B) demonstrates the P3 component in the *50% uncued action-effect* condition. These are included here to illustrate the P3 effect, given its topographic similarity to the P2. **C.** Difference waves, representing (top) *cued listening* minus *uncued listening,* and (bottom) *cued action-effect* minus *cued listening* (i.e., combined *100%* and *50%* variants). The dotted rectangle and accompanying topographic voltage map demonstrates the N2b analysis window, which appears to reflect reduced latency and amplitude of the P2 in *cued listening* compared with *uncued listening*. **D.** Orthogonal contrast relating to the effect of *cued self-generation* and accompanying topographic maps, including (left) *cued action-effect* and (right) combined *listening* conditions. Pink rings indicate analysis electrodes. **E.** Within-subject differences in mean P2 amplitude, including *cued action-effect* minus *cued listening* and *uncued listening* conditions by *stimulus identity prediction* (i.e., *100%* and *50%*). Error bars represent 95% confidence intervals.

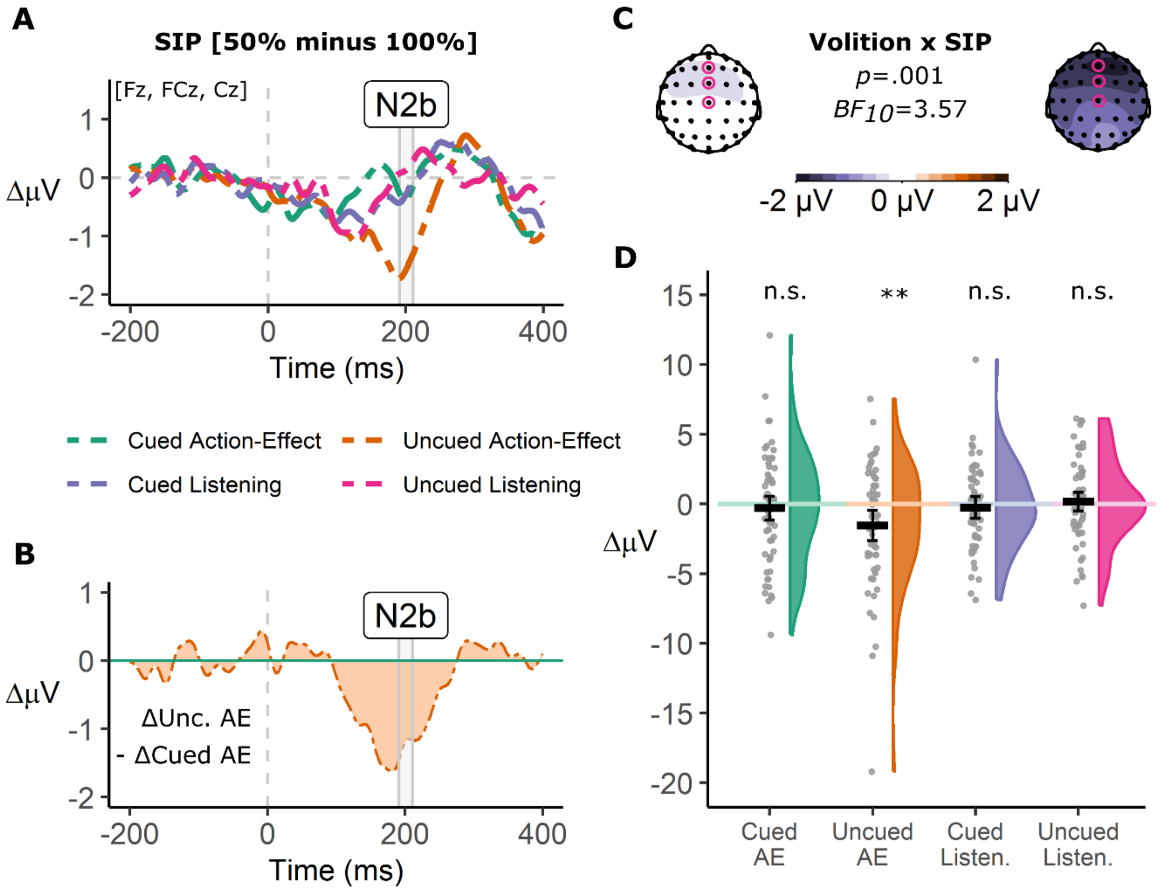
Note. n.s. = not significant, * $p < .05$, ** $p < .01$, *** $p < .001$

3.1.3. N2b

Results indicated a statistically significant effect of *task,* $F(2.46, 147.33) = 10.68$, $p < .001$, $\eta_p^2 = 0.15$, $BF_{10} = 10{,}101.45$. While the main effect of *stimulus identity prediction* was not significant, $F(0.80, 47.73) = 2.14$, $p = .149$, $\eta_p^2 = 0.03$, $BF_{10} = 0.34$, a statistically significant interaction was observed between *task* and *stimulus identity prediction*, $F(2.39, 143.18) = 4.71$, $p = .003$, $\eta_p^2 = 0.07$, $BF_{10} = 8.36$. Planned comparisons revealed significant effects associated with *cued self-generation,* $t(180) = -2.41$, $p = .017$, $d = -0.31$, $BF_{10} = 1{,}254.35$, and *temporal prediction*, $t(180) = -2.23$, $p = .027$, $d = -0.29$, $BF_{10} = 6{,}692.37$. The effect of *cued self-generation* was such that the *cued action-effect* condition had larger (i.e., more negative) N2b components compared with those of the *listening* conditions (i.e., *uncued listening* and *cued listening).* The temporal predictably effect was such that larger N2b components were observed in the *cued listening* condition compared with the *uncued listening* condition. It is important to note that the results of these planned comparisons should be interpreted with caution, given likely overlap between activity associated with the N2b and P2 components. While the identified peak latencies differed for each component in grand-averaged waveforms, there is overlap in the time periods typically associated with these components (i.e., as reflected in the windows that were used to identify peak latencies; see *Methods*). For this reason, our interpretation of the N2b effects was confined to interactions involving *stimulus identity prediction* (i.e., *100%* versus *50%*).

Importantly, a significant interaction was observed between *volition* and *stimulus identity prediction*, $t(240) = -3.28$, $p = 0.001$, $d = -0.49$, $BF_{10} = 3.57$. This interaction was such that tones with *50% stimulus identity prediction* elicited larger N2b amplitudes than those with *100% stimulus identity prediction* in the *uncued action-effect* condition (see Fig. 4). In contrast, no such effect was observed in relation to the other *task* conditions. Results from the sensitivity analysis, which utilised a peak based on the grand average of all 50% conditions, revealed no meaningful difference with regards to the results (i.e., no changes in the statistical significance).

Fig. 4: Analyses of N2b component amplitudes



A. Difference waves representing *50%* minus *100%* variants by task condition, including *cued action-effect, uncued action-effect, cued listening* and *uncued listening* condition. **B.** Differences in the effect of *stimulus identity prediction* (i.e., *50%* minus *100%*) between *cued action-effect* and *uncued action-effect* conditions. **C.** Statistical test outcomes relating to the interaction between *volition* and *stimulus identity prediction*. Accompanying topographic maps represent the effect of *stimulus identity prediction* (i.e., *50%* minus *100%*) for (left) combined *cued action-effect, cued listening* and *uncued* listening, and (right) *uncued action-effect.* Pink rings indicate analysis electrodes. **D.** Within-subject differences in mean N2b amplitude by *stimulus identity prediction* (i.e., *50%* minus *100%*)

for each *task* condition, including *cued action-effect, uncued action-effect, cued listening* and *uncued listening.* Error bars represent 95% confidence intervals.

Note. n.s. = not significant, ** $p < .01$

3.2. Inter-trial intervals

Descriptive statistics relating to ITI are provided by condition in Table A4. Following correction for non-sphericity using the Greenhouse-Geisser method (Geisser & Greenhouse, 1958), results from the ANOVA identified non-significant effects with respect to each factor, including *auditory stimuli,* $F(1.96, 117.60) = 0.07$, $p = .930$, $\eta_p^2 = 0.00$, $BF_{10} = 0.02$, *event activation,* $F(0.84, 50.70) = 0.35$, $p = .554$, $\eta_p^2 = 0.01$, $BF_{10} = 0.10$, and *visual stimuli,* $F(0.94, 56.39) = 1.81$, $p = .184$, $\eta_p^2 = 0.03$, $BF_{10} = 0.32$. Interactions were also found to be non-significant (see Table A5 for detail). Overall, these results reflect relative consistency in ITI across experimental conditions.

3.3. Power Analyses

The power ($1 - \beta$) of the sample ($N = 61$) to assess small, medium, and large effect sizes, was explored through post hoc analyses. Based on standardised reporting conventions (Cohen, 1988), the sample was sufficient to detect small ($\eta_p^2 = .01$), medium ($\eta_p^2 = .06$) and large ($\eta_p^2 = .14$) two-level repeated measures main effects with powers of .339, .973, and <.999, respectively. With regard to three-level main effects, the sample was found to achieve powers of .379, .993, and <.999, respectively.

4. Discussion

In the present study, we conducted an investigation into the influence of stimulus identity prediction on ERPs elicited by self- and externally-generated stimuli. The study was designed to evaluate and control for effects relating to differences in temporal predictability, serving to address prior methodological limitations in this regard. We also sought to assess a potential relationship between the attentional suppression of outcomes to stimulus-driven movement (i.e., as reflected in N1 amplitudes; Harrison et al., 2023) and reduced levels of misprediction sensitivity (i.e., as reflected in N2b amplitudes). In the following section, we provide a summary of key findings and synthesis with existing literature.

The experiment facilitated an assessment of effects associated with cued self-generation on N1 and P2 amplitudes, as well the potential influence of action-effect predictability on these components. N1 amplitudes in the *cued action-effect* condition were not found to differ from those elicited by externally-generated stimuli (i.e., the effect of *cued self-generation* was not significant) and the corresponding Bayes factor suggested substantial evidence in favour of mean amplitudes not differing in this regard. This finding is consistent with previous research demonstrating that sensory attenuation of the N1 is diminished when the temporal predictability of self – and externally-generated stimuli is made similar (Bolt & Loehr, 2021, 2023; Egan et al., 2023; Sowman et al., 2012).

The effect of *cued self-generation* was associated with a significant attenuation of P2 amplitudes. This finding is in accordance with our hypothesis, and corroborates other recent evidence of a robust effect of self-generation on P2 amplitudes (e.g., Bolt & Loehr, 2021, 2023; Harrison et al., 2021). Unlike the effect of self-generation on N1 amplitudes, the present findings suggest that suppression of P2 amplitudes (i.e., for self- versus externally-generated stimuli) holds when also controlling for the effects of temporal predictability. As a reduction in P2 amplitudes has been attributed to activity involving the termination of selective attention (Crowley & Colrain, 2004; García-Larrea et al., 1992), these findings may reflect preparedness to disengage attention to self-generated stimuli. It is worth noting that research has previously associated reduced P2 amplitudes for self-generated stimuli with one's sense of agency and control (Harrison et al., 2021; Timm et al., 2016). While findings with respect to the P2 may reflect conscious evaluation of one's agency in the production of stimuli, this interpretation is not necessarily incompatible with attribution of the observed effects to mechanisms involving attentional control. For example, reduced P2 amplitudes may reflect termination of selective attention to stimuli that one recognises consciously as having been self-generated. Such a relationship may be consistent with theories emphasising the interrelatedness of attention, prediction and agency (see Brown et al., 2013; Clark, 2013).

In accordance with our hypothesis, the results replicate previous research (e.g., Lange, 2009; Weiskrantz et al., 1971) in demonstrating reduced N1 amplitudes (i.e., relative positivity) to stimuli when these were made predictable in time (i.e., *cued listening* versus *uncued listening*). Interestingly, the suppressive effect of temporal prediction on N1 amplitudes was followed by relative negativity that was statistically significant at its peak approximately 200 ms post-stimulus (i.e., the N2b analysis window; see Fig. 3C). This was not followed by an apparent P3 and was therefore unlikely to reflect influences associated with the N2b component, which requires attention to an eliciting stimulus and is always accompanied by a P3 (Folstein & Van Petten, 2008; Pritchard et al., 1991). As the P2 component has been found to be larger and occur later in lower states of arousal (Colrain et al., 2000), the effect may instead represent heightened arousal based on the cueing of externally-generated stimuli.

In contrast with our hypothesis and recent findings (Harrison et al., 2023; Harrison et al., 2021), no apparent difference was observed in N1 amplitudes between the *cued action-effect* and *uncued action-effect* conditions. Although the reasons for a diminished effect in the present study are not immediately clear, it is noteworthy that our investigation involved longer ITIs than in previous studies. This was due to the inclusion of prompts, which reminded participants to slow down following trials with an ITI less than 2000 ms. Research has indicated that action-effects associated with stimulus-driven movement elicit reduced N1 amplitudes as a result of attentional suppression (Harrison et al., 2023). It is possible that longer ITIs reduced participants' levels of arousal. As lower levels of arousal are believed to diminish the effects of attention (see Coull, 1998), this may account for a reduction in the effect of action cueing on N1 amplitudes. Future research may therefore be needed to examine the possibility that effects associated with action cueing on N1 amplitudes are moderated by the interval between self-generated stimuli and the reasons for such an effect.

Analyses of effects associated with *stimulus identity prediction* (i.e., contrasting *100%* and *50%* variants of each condition) are informative to understanding the influence of stimulus and action-effect predictability on sensory processing. The effect of *stimulus identity prediction* was found to be significant with respect to N1 amplitudes, reflecting a reduced primary cortical response to stimuli in blocks that contained trials with a single tone frequency. This finding was in accordance with our hypothesis and consistent with Baess et al. (2008), who observed a main effect of tone frequency prediction in which predictable self- and externally-generated stimuli were suppressed. In contrast with the results from Baess et al. (2008), our findings did not reveal differences in the effects of stimulus identity prediction on N1 amplitudes in self- versus externally-generated conditions. In particular, the non-significant *stimulus identity prediction* x *cued self-generation* interaction suggested that N1 amplitudes were not differentially affected by tone frequency prediction in the *cued action-effect* and externally-generated conditions (i.e., *cued listening* and *uncued listening*). Similarly, the *stimulus identity prediction* x *volition* interaction (i.e., contrasting the effect of *stimulus identity prediction* in the *uncued action-effect* condition with each of the other conditions) was not significant with respect to its effect on N1 amplitudes. These findings are consistent with other recent evidence that N1 amplitudes are not influenced by action-effect predictability (Bednark et al., 2015; Dogge, Hofman, et al., 2019; Harrison et al., 2023; Le

Bars et al., 2019), and are contrary to the attribution of N1 sensory attenuation to the effects of motor-based prediction.

There are several potential explanations for the significant main effect of *stimulus identity prediction* on N1 amplitudes (i.e., contrasting 100% and 50% variants of each condition). Firstly, this effect may represent an attenuation of the auditory N1 component based on generalised (i.e., non-motor) predictions regarding the identity of ensuing tones. As more specific predictions were facilitated in the 100% conditions, compared to the 50% conditions, these may have contributed to the observed suppression of N1 amplitudes. Alternatively, the effect of *stimulus identity prediction* may be consistent with repetition suppression, whereby a reduction in neural response is observed upon repeated presentation of the same stimulus (Desimone, 1996). This effect is believed to reflect the refined engagement of neural populations (Wiggs & Martin, 1998) and desensitisation through neuronal fatigue (Grill-Spector et al., 2006). The observed main effect of stimulus identity prediction may therefore be attributable to generalised (i.e., non-motor) prediction, repetition suppression, or some combination of each. Further research is needed to delineate these possibilities.

In accordance with our hypothesis, findings with respect to the N2b demonstrated differences in misprediction sensitivity based on whether participants had agency in determining *when* to generate movement. In particular, we observed a significant interaction between *stimulus identity prediction* and *volition* (i.e., contrasting *uncued action-effect* with each of the other conditions) on N2b component amplitudes. This involved larger N2b amplitudes in the *50%* variant of the *uncued action-effect* condition compared with the *100%* variety (see Fig. 4). In contrast, no such effect was evident with respect to the *cued action-effect, cued listening* or *uncued listening* conditions. The interaction between *stimulus identity prediction* and *cued self-generation* (i.e., contrasting *cued action-effect* with externally-generated conditions) was not found to be significant and the Bayes factor indicated substantial evidence in favour of a null effect.

These findings extend the work of Le Bars et al. (2019), who demonstrated differences in the neurophysiological response to mispredicted action-effects based on one's agency in deciding *what* movement to produce. In particular, results from the present investigation reflect heightened sensitivity to mispredicted action-effects when movement was uncued with respect to timing (i.e., selecting *when* to act) despite an absence of agency over the nature of such action (i.e., selecting *what* movement to undertake). In contrast, and in accordance with Le Bars et al. (2019), misprediction sensitivity was diminished with respect to the outcomes of stimulus-driven movement. As highlighted by Le Bars et al. (2019), differences in the N2b based on *stimulus identity prediction* appears to reflect the updating of one's association between a motor action and its effects. This process, which Le Bars et al. (2019) describe as an 'effect-update', appears therefore to be contingent on one's agency over *what* movement is produced or *when*.

In conjunction with previous findings, our results may provide insight into the manner by which intention-based action-effects are distinguished from other events. Specifically, a relationship may be posited between the attentional suppression observed in relation to outcomes of stimulus-driven movement (i.e., of N1 amplitudes; Harrison et al., 2023) and diminished misprediction sensitivity (i.e., N2b effects in the present study). This notion is consistent with research demonstrating that attention acts as a form of gain modulation on prediction errors (Kok et al., 2012; see Schröger et al., 2015). Findings may therefore provide evidence in support of mechanisms proposed by Brown et al. (2013), whereby a reduction in attention to the outcomes of movement reduces the precision weighting of resultant stimuli. Significantly, our findings suggest differing effects of stimulus-driven and intention-based movement. While the outcomes of volitional movement may be compared with its predicted action-effects, attentional suppression of the outcomes to stimulus-driven action may preclude these from subsequent processing. Such a mechanism might serve to differentiate the outcomes of movement that is based on one's explicit intentions from those that are produced in response to external stimuli and therefore ambiguous with respect to self-generation.

The study contained several limitations that warrant acknowledgment. Firstly, there are limitations to the method we used to control for visual and motor activity (i.e., subtracting waveforms associated with tasks that lacked sound stimuli but were otherwise identical). While common in electrophysiological studies of sensory attenuation (e.g., Martikainen et al., 2005; Mifsud et al., 2016; Mifsud & Whitford, 2017; Oestreich et al., 2015), this technique assumes linear summation of activity relating to visual, motor and auditory stimuli. It is important to acknowledge that interactions between the presence or absence of sound stimuli and participants' engagement in the task (e.g., the forcefulness of button presses or allocation of attention) may jeopardise the validity of this assumption (see Neszmélyi & Horváth, 2017). Further research may be needed to mitigate these potential confounds through alternative techniques that more accurately isolate the effects of interest (e.g., through intracranial recordings or functional magnetic resonance imaging).

The present investigation was also limited by challenges with respect to disentangling the effects associated with ERP components that had overlapping latencies. While the collapsed localizer method was used for consistency with other recent experiments (e.g., Harrison et al., 2023; Harrison et al., 2021), it is important to acknowledge that this approach can sometimes bias results when component latencies differ between conditions (Luck & Gaspelin, 2017). Differences in component latencies in the present investigation (e.g., earlier latency of N1 amplitudes in *cued listening* compared with *uncued listening*; see Fig. 2A) may have therefore influenced results. Another significant challenge with respect to differentiating components pertained to the interpretation of effects associated with *temporal prediction*. Although the *cued listening* conditions were found to be more negative than the *uncued listening* conditions within the N2b analysis window (see Fig. 3C), we have tentatively attributed these effects to differences in the P2 as this was supported by a stronger theoretical basis. Future research may be needed to replicate these findings in a manner that distinguishes more effectively between these effects, including through cluster-based permutation testing for example (see Maris & Oostenveld, 2007).

Finally, despite our direct comparison of the present findings with those of Le Bars et al. (2019), it is important to acknowledge differences in the manipulation of stimulus identity prediction across the two studies. In particular, Le Bars et al. (2019) compared predictable stimuli (i.e., 100% contingency) with infrequent and therefore *mispredicted* stimuli (i.e., 23% contingency). Our use of 50% contingency in the less predictable condition meant that action-effects were neither highly predicted nor unpredicted. Further research is needed to explore the sensitivity of the observed effects to changes in the *degree* to which stimuli are unpredictable.

5. Conclusions

Although predictable tone frequencies were associated with a generalised reduction in N1 component amplitudes, our findings suggest that the effect of predictability did not differ between self- and externally-generated stimuli. This finding suggests that action-effect predictions may not be involved in sensory attenuation of the N1 component for self-generated stimuli, contrary to IFM accounts of this phenomenon. Consistent with recent findings (Bolt & Loehr, 2021, 2023; Egan et al., 2023; Harrison et al., 2021), differences in N1 amplitude were not observed between self- and externally-generated stimuli with similar levels of temporal predictability. In contrast, a significant reduction in P2 amplitudes was observed for self- versus externally-generated stimuli. This was in accordance with recent evidence that, in contrast with the N1, self-generated stimuli are robustly associated with reduced P2 amplitudes when the temporal predictability of self- and externally-generated stimuli is made similar (Bolt & Loehr, 2021, 2023; Harrison et al., 2021). Effects pertaining to the P2 may implicate differences in attentional control, including processes involved in the termination of implicit attention to self-generated events.

Importantly, findings from the present study demonstrate that action-effect predictions influence N2b amplitudes when movement is uncued with respect to timing. In contrast, action-effect predictions do not appear to be subject to self-monitoring when movement is enacted in response to external stimuli. These findings indicate differential processing of action-effect predictions based on one's agency over *when* action is initiated that parallel findings with respect to control over *what* movement is enacted (Le Bars et al., 2019). Recent evidence suggests that the outcomes of stimulus-driven movement are subject to attentional suppression that reduces the associated primary cortical response (i.e., N1 amplitudes; Harrison et al., 2023). In addition to its potential role in sensory attenuation, we propose that this attentional suppression may diminish the self-monitoring of action-effects that result from stimulus-driven movement. Together, these mechanisms might play a central role in distinguishing self- from externally-generated stimuli and in supporting one's sense of agency over the outcomes of intentional movement. While findings from the present study highlight limitations to current theoretical accounts of sensory attenuation, they provide promising new avenues for investigation of distinct sensorimotor processing in volitional and stimulus-driven movement.

6. Data Availability Statement

Data and analysis scripts from this investigation are available, and can be downloaded at https://github.com/a-w-harrison/action-effect-prediction-error-monitoring. This includes processed and epoched EEG data for analysis electrodes by condition, as well as mean component amplitudes by condition and participant.

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8. Author Contributions

A.W.H: Conceptualisation, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualisation, Project Administration. **B.K.C:** Conceptualisation, Writing – Review & Editing. **T.J.W:** Methodology, Software, Validation, Resources, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition.

9. Competing Interests

The authors have no competing interests to declare.

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11. Appendix

Table A1

Descriptive Statistics by Analysis Condition

		N1		P2		N2b	
SIP	Task	*M*	*SD*	*M*	*SD*	*M*	*SD*
100%	Uncued Self-gen.	-3.95	3.94	1.11	3.05	0.64	3.48
	Cued Self-gen.	-3.98	3.66	0.93	3.53	0.17	4.25
	Uncued Listening	-4.80	3.41	2.76	3.07	2.04	3.10
	Cued Listening	-3.82	3.37	0.39	2.90	0.74	2.77
50%	Uncued Self-gen.	-4.60	3.81	0.11	3.36	-1.10	4.03
	Cued Self-gen.	-4.65	4.25	1.21	4.53	-0.14	4.73
	Uncued Listening	-5.34	3.19	2.46	2.73	2.44	3.87
	Cued Listening	-4.51	3.51	1.96	2.50	0.72	3.09

Note. SIP = Stimulus Identity Prediction

Table A2

ANOVA Analysis of Component Amplitudes

		df_{num}	df_{den}	SS_{num}	SS_{den}	F	p	η_p^2	BF_{10}
N1	Intercept	0.98	58.85	9,682.97	4,359.78	133.26	<.001	0.69	1.00
	SIP	0.86	51.72	49.24	249.14	11.86	.001	0.17	9.12
	Task	2.94	176.56	62.69	1,291.94	2.91	.036	0.05	0.81
	SIP x Task	2.59	155.17	0.43	620.21	0.04	.989	0.00	0.21
P2	Intercept	0.74	44.38	1,263.58	1,722.12	44.02	<.001	0.42	1.00
	SIP	0.77	45.95	15.09	542.04	1.67	.201	0.03	0.33
	Task	2.22	133.15	316.11	2,051.31	9.25	<.001	0.13	1,952.55
	SIP x Task	2.30	137.84	25.46	774.34	1.97	.120	0.03	0.25
N2b	Intercept	0.82	49.11	231.76	2,488.19	5.59	.021	0.09	1.00
	SIP	0.80	47.73	21.04	589.62	2.14	.149	0.03	0.34
	Task	2.46	147.33	453.50	2,547.14	10.68	<.001	0.15	10,101.45
	SIP x Task	2.39	143.18	79.37	1,010.71	4.71	.003	0.07	8.36

Note. SIP = Stimulus Identity Prediction

Table A3

Planned contrasts and interactions

		Est.	*SE*	95% *CI* Lower	95% *CI* Upper	*df*	*t*	*p*	*d*	BF_{10}
N1	Volition	0.06	0.09	-0.11	0.23	180	0.72	.472	0.11	0.19
	Self-gen.	0.11	0.12	-0.13	0.35	180	0.90	.369	0.12	0.25
	Temp. Predict	0.49	0.21	0.08	0.90	180	2.34	.020	0.30	33.62
	Volition x SIP	-0.00	0.10	-0.20	0.19	240	-0.05	.964	-0.01	0.16
	Self-gen. x SIP	-0.02	0.14	-0.29	0.26	240	-0.13	.896	-0.02	0.17
	Temp. Predict x SIP	-0.08	0.24	-0.55	0.40	240	-0.32	.751	-0.04	0.11
P2	Volition	-0.22	0.11	-0.44	-0.01	180	-2.09	.038	-0.31	1,223.77
	Self-gen.	-0.54	0.15	-0.84	-0.24	180	-3.57	<.001	-0.46	1,142.17
	Temp. Predict	-0.21	0.26	-0.72	0.31	180	-0.78	.435	-0.10	0.58
	Volition x SIP	-0.22	0.12	-0.46	0.02	240	-1.78	.077	-0.27	0.40
	Self-gen. x SIP	0.21	0.17	-0.13	0.55	240	1.21	.229	0.16	0.26
	Temp. Predict x SIP	-0.05	0.30	-0.63	0.54	240	-0.16	.874	-0.02	0.19
N2b	Volition	-0.09	0.12	-0.32	0.15	180	-0.72	.475	-0.11	51.43
	Self-gen.	-0.41	0.17	-0.74	-0.08	180	-2.41	.017	-0.31	1,254.35
	Temp. Predict	-0.65	0.29	-1.22	-0.08	180	-2.23	.027	-0.29	6,692.37

Volition x SIP	-0.44	0.13	-0.71	-0.18	240	-3.28	.001	-0.49	3.57
Self-gen. x SIP	-0.17	0.19	-0.54	0.20	240	-0.88	.379	-0.11	0.21
Temp. Predict x SIP	-0.21	0.33	-0.86	0.44	240	-0.63	.528	-0.08	0.24

Note. SIP = Stimulus Identity Prediction

Table A4

ITI and Trial Count by Experimental Condition

			ITI			Trial Count		
Auditory Stimuli	Event Activation	Visual Stim.	*M*	*SD*	*Min.*	*M*	*SD*	*Min.*
Motor/Visual	Self-gen.	Cued	2,933.40	375.15	2,128.74	68.49	2.00	60
	Self-gen.	Uncued	2,916.04	356.39	2,120.75	66.89	3.49	50
	External	Cued	2,897.88	346.76	2,131.30	67.08	5.26	38
	External	Uncued	2,942.91	310.82	2,163.67	67.02	4.56	40
100%	Self-gen.	Cued	2,910.41	313.36	2,120.76	68.05	3.38	49
	Self-gen.	Uncued	2,922.47	340.13	2,139.94	67.34	3.70	50
	External	Cued	2,944.58	308.71	2,120.75	67.61	3.89	49
	External	Uncued	2,947.29	342.59	2,120.78	67.64	4.57	40
50%	Self-gen.	Cued	2,955.33	354.33	2,125.44	68.39	2.44	57
	Self-gen.	Uncued	2,988.76	324.24	2,280.41	67.66	4.96	39
	External	Cued	2,934.07	323.45	2,126.85	68.16	3.25	48
	External	Uncued	2,918.98	315.04	2,174.28	67.74	3.85	48

Table A5

ANOVA Analysis of Inter-trial Intervals

	df_{num}	df_{den}	SS_{num}	SS_{den}	F	P	η_p^2	BF_{10}
Intercept	0.99	59.69	6.30E+09	6.29E+07	6,016.38	<.001	0.99	1.00
Auditory Stimuli	1.96	117.60	5.17E+03	4.28E+06	0.07	.930	0.00	0.02
Event Activation	0.84	50.70	1.35E+04	2.28E+06	0.35	.554	0.01	0.10
Visual Stimuli	0.94	56.39	8.13E+04	2.70E+06	1.81	.184	0.03	0.32
Auditory Stimuli x Event Activation	1.99	119.37	1.05E+04	2.93E+06	0.21	.807	0.00	0.04
Auditory Stimuli x Visual Stimuli	1.96	117.60	1.01E+03	2.64E+06	0.02	.977	0.00	0.03
Event Activation x Visual Stimuli	0.84	50.70	3.46E+04	1.02E+06	2.03	.159	0.03	0.21
Auditory Stimuli x Event Activation x Visual Stimuli	1.88	112.79	4.49E+04	3.57E+06	0.75	.472	0.01	0.11