Title:

Action-effect prediction in volitional and stimulus-driven movement: An investigation

of error monitoring

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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 produced with less regard for its specific effects. Differing use of action-effect predictions in each form of movement may influence processes to which they are commonly attributed, including sensory attenuation and error monitoring. 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 predictability 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 error monitoring, we compared the influence of stimulus predictability on N2b component amplitudes. A significant interaction was found to reflect error monitoring of sound produced by volitional action that was absent with respect to other stimuli. In light of recent evidence that attentional suppression may attenuate the primary cortical response of outcomes to stimulus-driven movement, we propose that this mechanism might also serve to diminish prediction error signals for such action. As such, these effects may represent important features of sensorimotor processing that assist in differentiating stimuli on the basis of self-generation and intentionality.

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 reduce the distraction associated with sensations that result from an organism's own movement, allowing it to remain vigilant to stimuli that reflect changes in its environment (see Crapse & Sommer, 2008). Sensory attenuation is thought to be adaptive because, although representations of externally-generated events rely on information arriving through sensory channels, self-generated stimuli may be predicted based on the motor-activities through which they are produced. This notion has contributed to theoretical accounts that suggest self-generated sensations are suppressed *based on* the predicted outcomes of movement (Wolpert, 1997). For example, 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).

In addition to prioritising externally-generated sensations, computational mechanisms within the IFM are believed to support the selection and enactment of movement based on its predicted outcomes (Wolpert et al., 1995). According to this account, dynamic control is facilitated through the detection of discrepancies between one's predicted sensations and those arising in response to movement (Miall & Wolpert, 1996). The notion that action-effect predictions guide movement has been a central tenet to several other influential theories of

motor control, including classical ideomotor theory (James, 1890; see review by Shin et al., 2010) and more contemporary perspectives within the active inference literature (Friston, 2009; Friston et al., 2010). This mechanism is also believed to 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 over 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 primary 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 involving the N1, research has yielded discrepant findings with respect to the role of action-effect prediction. 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; Klaffehn et al., 2019; 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 also 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.

Recent evidence suggests that attentional suppression may also play a role in reducing N1 amplitudes to some forms of self-generated stimuli (Harrison et al., 2023). 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 is believed to reflect active suppression of spatially-oriented attention and 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 mechanisms of sensorimotor processing, research has demonstrated differences in electrophysiological markers of error monitoring between 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 error monitoring of the outcomes of movement when an agent has chosen *what* movement to undertake.

Several questions are raised in association with the reviewed literature. Firstly, methodological confounds and discrepancies in previous findings warrant investigation into the role of action-effect predictability in sensory attenuation. Given that the sensory attenuation literature has commonly focused on effects involving the N1, and have attributed these to predictive mechanisms within the IFM, it would be informative to compare such effects with those pertaining to the predictability of externally-generated stimuli. 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 error monitoring (i.e., as reflected by differences in N2b amplitudes to predicted and unpredicted stimuli) based on whether participants have chosen *what* action to undertake. 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. 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 provide an exploratory investigation into the influence of stimulus predictability 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). In the case of externally-generated tones, the presence or absence of visual cues supported an assessment of the effects of temporal predictability. To assess effects relating to stimulus predictability, 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% contingency), trials in the intermixed two-tone variant involved the presentation of a tone frequency with 50% contingency. As such, comparison of these conditions facilitated an assessment of the effects of predictability on components of the evoked response. Further detail is provided in the *Design* section (below).

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). 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 were positioned according to the extended 10:20 layout. 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°).

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. Brief reminders were displayed above the fixation line from 400 ms to 800 ms post-

stimulus following trials in which participants had pressed with less than two seconds

between trials. This reminder, which asked participants to "slow down", was infrequently

required and consistent across variants of the *uncued* condition ($M = 0.74$, $SD = 1.17$).

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. 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. 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%* sequences, 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.
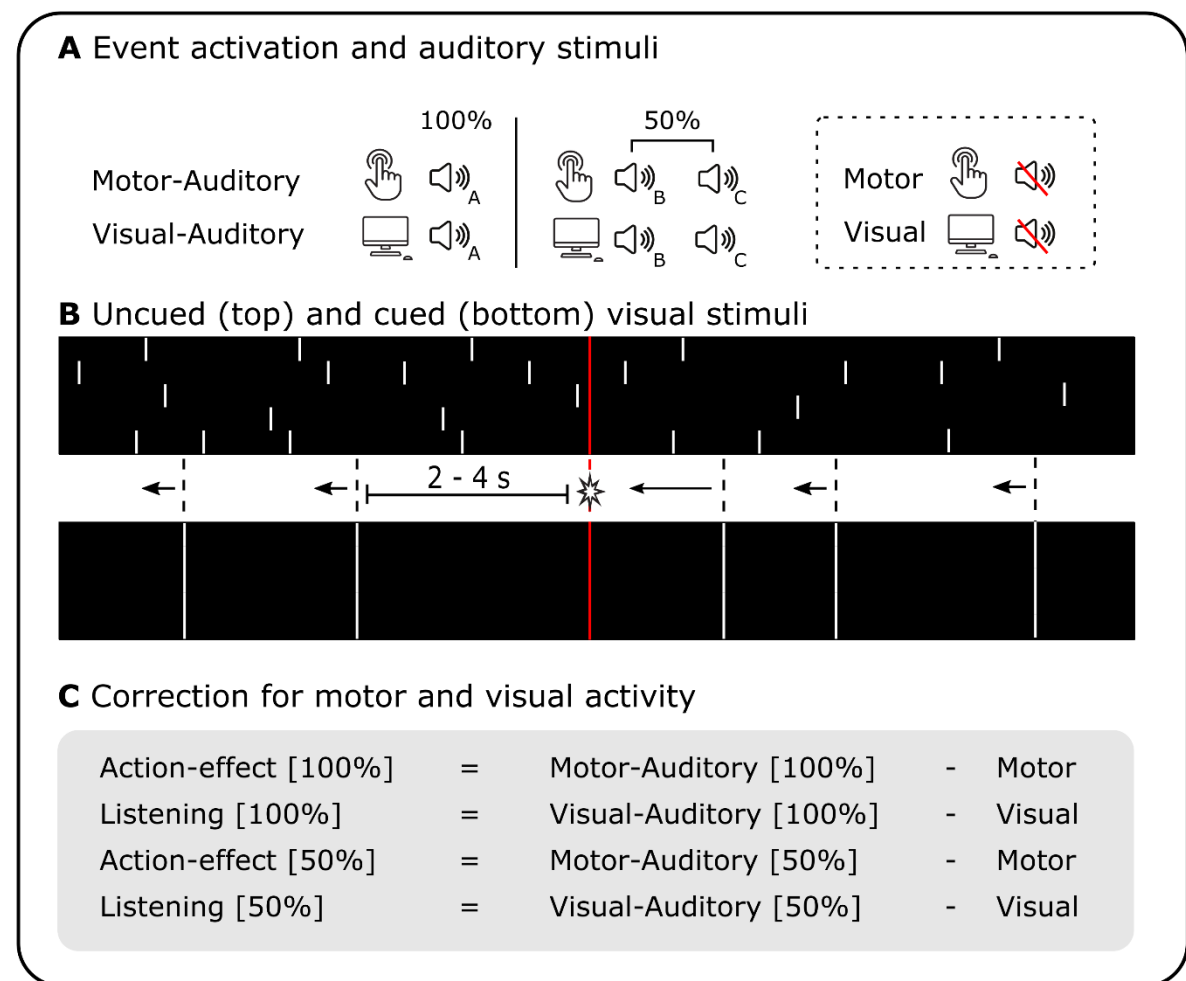
2.2.2. *Cued conditions*

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. 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. The order of blocks was pseudorandomised, such that the *uncued motor-auditory* (i.e., 100% and 50% variants) and *uncued silent* 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.

Fig. 1: Protocol schematic and visual stimuli

A Event activation and auditory stimuli

B Uncued (top) and cued (bottom) visual stimuli

2 - 4 s

C Correction for motor and visual activity

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 longer vertical 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 longer 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.

2.3. 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). Baseline correction was applied using

average recordings in the 200 ms prior to each event. 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. 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. 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. 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. When taken as the most negative local minimum between 150 ms and 300 ms post-auditory, the N2b peak was found to have occurred 200.7 ms post-stimulus. An apparent P3 component was also observed in the *50% uncued action-effect* condition, with a latency of 279.3 ms when taken as the most positive local maximum between 250 ms and 350 ms.

3. Results

3.1. 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. 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.

Three 2 x 4 repeated measures ANOVAs were used to investigate the main effects of *contingency* (i.e., *100%* versus *50%*) and *task*, as well as their interaction, on N1, P2 and N2b amplitudes respectively. 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]), *self-generation* ([0, 2, -1, -1]) and *temporal predictability* ([0, 0, -1, 1]). 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 *contingency* 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 $1/\sqrt{2}$ (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).

3.1.1. N1

The ANOVA revealed statistically significant main effects of both *contingency*, $F(0.86, 51.72) = 11.86$, $p = .001$, $\eta_p^2 = 0.17$, $BF_{10} = 9.18$, and *task*, $F(2.94, 176.56) = 2.91$, $p = .036$, $\eta_p^2 = 0.05$, $BF_{10} = 1.76$ (see Fig. 2). Planned comparisons indicated a significant effect of *temporal predictability* (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 *self-generation* were not found to be significant (see Table A3 for detail), nor were interactions between the effect of *contingency* and each of the planned comparisons. This included the *temporal predictability* x *contingency* interaction, $t(240) = -0.32$, $p = .751$, $d = -0.04$, $BF_{10} = 0.11$, and the *self-generation* x *contingency* interaction, $t(240) = -0.13$, $p = .896$, $d = -0.02$, $BF_{10} = 0.17$. In both cases, the associated Bayes factor indicated substantial evidence in favour of a null effect (see Jeffreys, 1998).
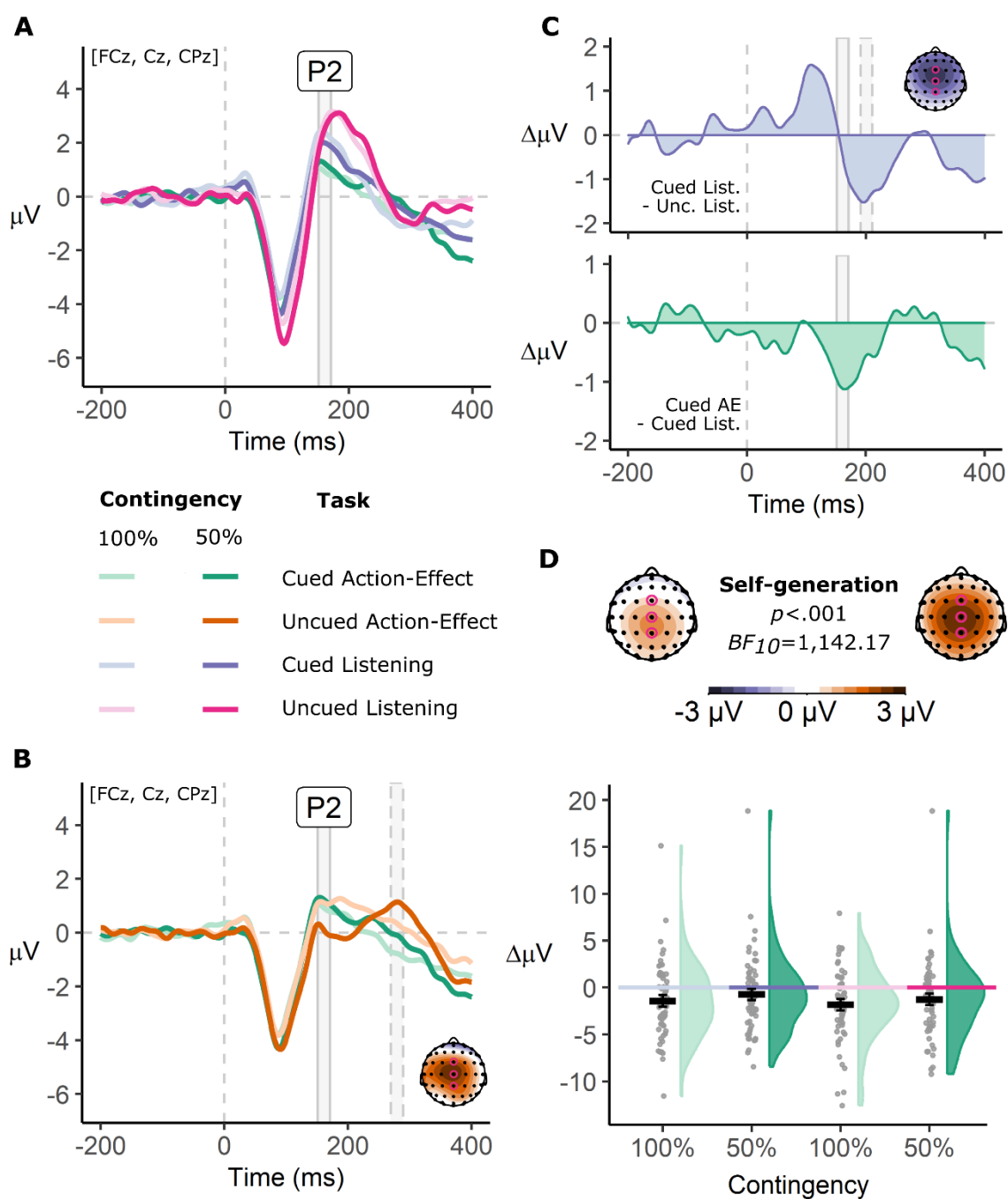
Fig. 2: Analyses of N1 component amplitudes
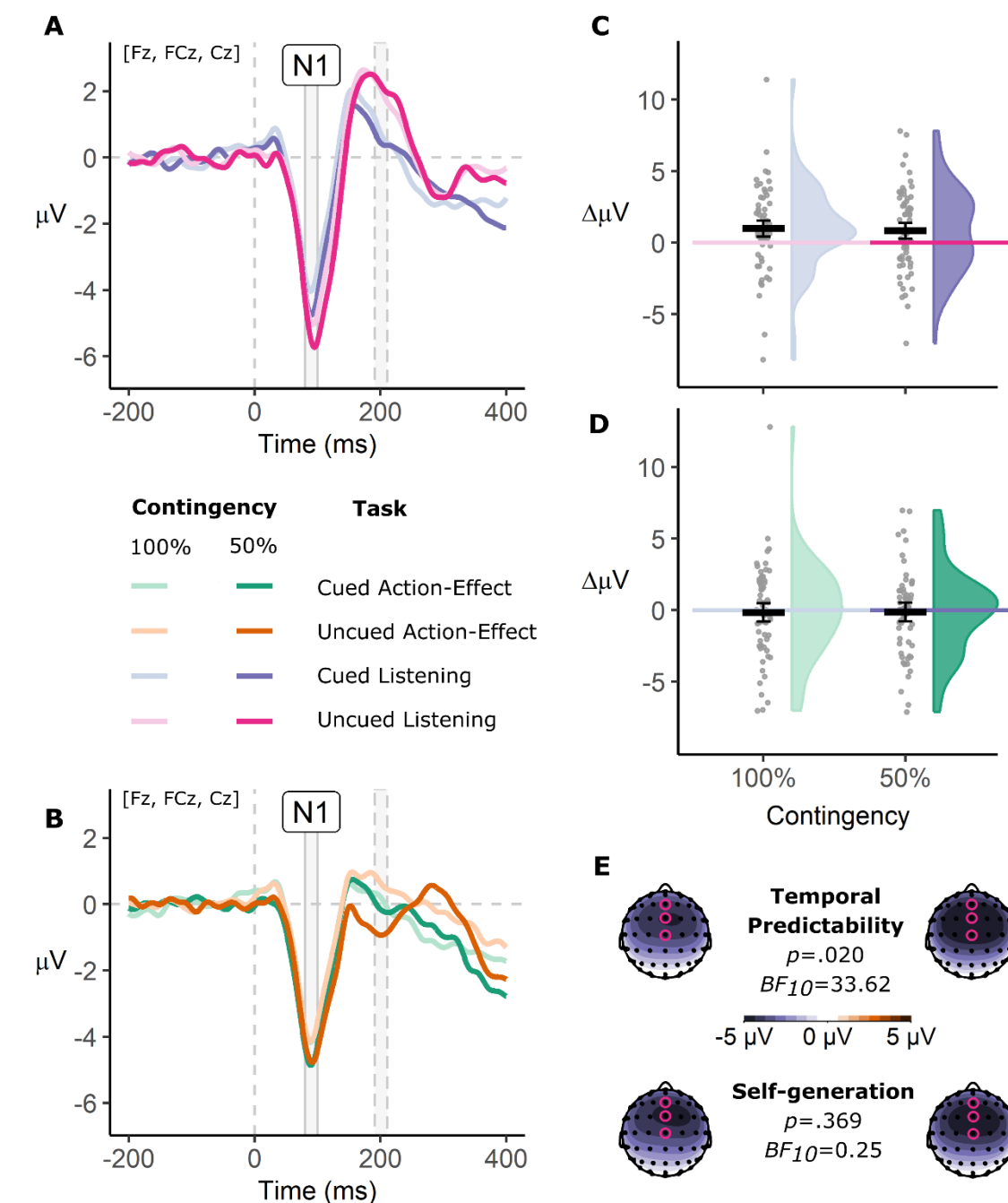
A-B. Pooled grand-averaged recordings at Fz, FCz and Cz, demonstrating mean amplitudes

for the (A) *listening* conditions and (B) *action-effect* conditions, by *contingency* (i.e., *100%*

and *50%*). Dotted rectangles mark the window representing N2b component analyses,

which were based on same pooled electrodes as the N1. **C-D.** Within-subject differences in

mean N1 amplitudes between (C) *cued listening* and *uncued listening* and (D) *cued action-effect* and *cued listening,* by *contingency* (i.e., *100%* and *50%*). Error bars represent 95% confidence intervals. **E.** Orthogonal contrasts relating to the effects of *temporal predictability* and *self-generation*. Accompanying topographic maps demonstrate the contrast in N1 distribution between the (top left) *cued listening* and (top right) *uncued listening* conditions, and between (bottom left) *cued action-effect* and (bottom right) combined *listening* conditions. Pink rings indicate analysis electrodes.

3.1.2. P2

The ANOVA revealed a statistically significant effect of *task* on P2 amplitude, $F(2.22, 133.15) = 9.25$, $p < .001$, $\eta_p^2 = 0.13$, $BF_{10} = 334,906.58$ (see Fig. 3). In contrast, non-significant effects were observed with respect to *contingency*, $F(0.77, 45.95) = 1.67$, $p = .201$, $\eta_p^2 = 0.03$, $BF_{10} = 0.23$, and the interaction between *task* and *contingency*, $F(2.30, 137.84) = 1.97$, $p = .120$, $\eta_p^2 = 0.03$, $BF_{10} = 0.07$. Planned comparisons revealed statistically significant effects of both *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 *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. Other planned comparisons and interactions with the effects of *contingency*, 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 *contingency* (i.e., *100%* and *50%*). The dotted rectangle and accompanying topographic map in (B) demonstrates the P3 component (279 ms post-

stimulus) 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 contrasts relating to the effect of *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 *contingency* (i.e., *100%* and *50%*). Error bars represent 95% confidence intervals.

3.1.3.   N2b

To investigate effects involving the N2b component, another 2 x 4 repeated measures ANOVA was conducted. This again supported examination of the main effects of *contingency* and *task*, as well as their interaction. To reiterate, the effect of *contingency* compared the response evoked by tones with *100%* and *50%* contingencies. This facilitated an assessment of differences based on whether tone frequencies could be accurately predicted on each given trial or not. The effect of *task* compared evoked responses across the different types of event activation (i.e., *uncued action-effect, cued action-effect, uncued listening* and *cued listening*). Orthogonal contrasts supported the investigation of effects associated with *volition* ([3, -1, -1, -1]), *self-generation* ([0, 2, -1, -1]) and *temporal predictability* ([0, 0, -1, 1]). Mauchly's test identified non-sphericity within the ANOVA model (Mauchly, 1940),

which was again corrected using the Greenhouse-Geisser method (Geisser & Greenhouse, 1958).

Results indicated a statistically significant effect of *task,* $F(2.46, 147.33) = 10.68$, $p <$ .001, $\eta_p^2 = 0.15$, $BF_{10} = 4{,}336{,}194.87$. While the main effect of *contingency* was not significant, $F(0.80, 47.73) = 2.14$, $p = .149$, $\eta_p^2 = 0.03$, $BF_{10} = 0.26$, a statistically significant interaction was observed between *task* and *contingency*, $F(2.39, 143.18) = 4.71$, $p = .003$, $\eta_p^2 = 0.07$, $BF_{10} = 0.42$. Planned comparisons revealed significant effects associated with *self-generation,* $t(180) = -2.41$, $p = .017$, $d = -0.31$, $BF_{10} = 1{,}254.35$, and *temporal predictability*, $t(180) = -2.23$, $p = .027$, $d = -0.29$, $BF_{10} = 6{,}692.37$. The effect of *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 the overlap between N2b and P2 component latencies. For this reason, our interpretation of the N2b effects was confined to interactions involving *contingency* (i.e., *100%* versus *50%*).

Importantly, a significant interaction was observed between *volition* and *contingency,* $t(240) = -3.28$, $p = 0.001$, $d = -0.49$, $BF_{10} = 3.57$. This interaction was such that tones with *50%* contingency elicited larger N2b amplitudes than those with *100%* contingency in the *uncued action-effect* condition (see Fig. 4)*. In contrast, no such effect was observed in relation to the other *task* conditions.

Fig. 4: Analyses of N2b component amplitudes
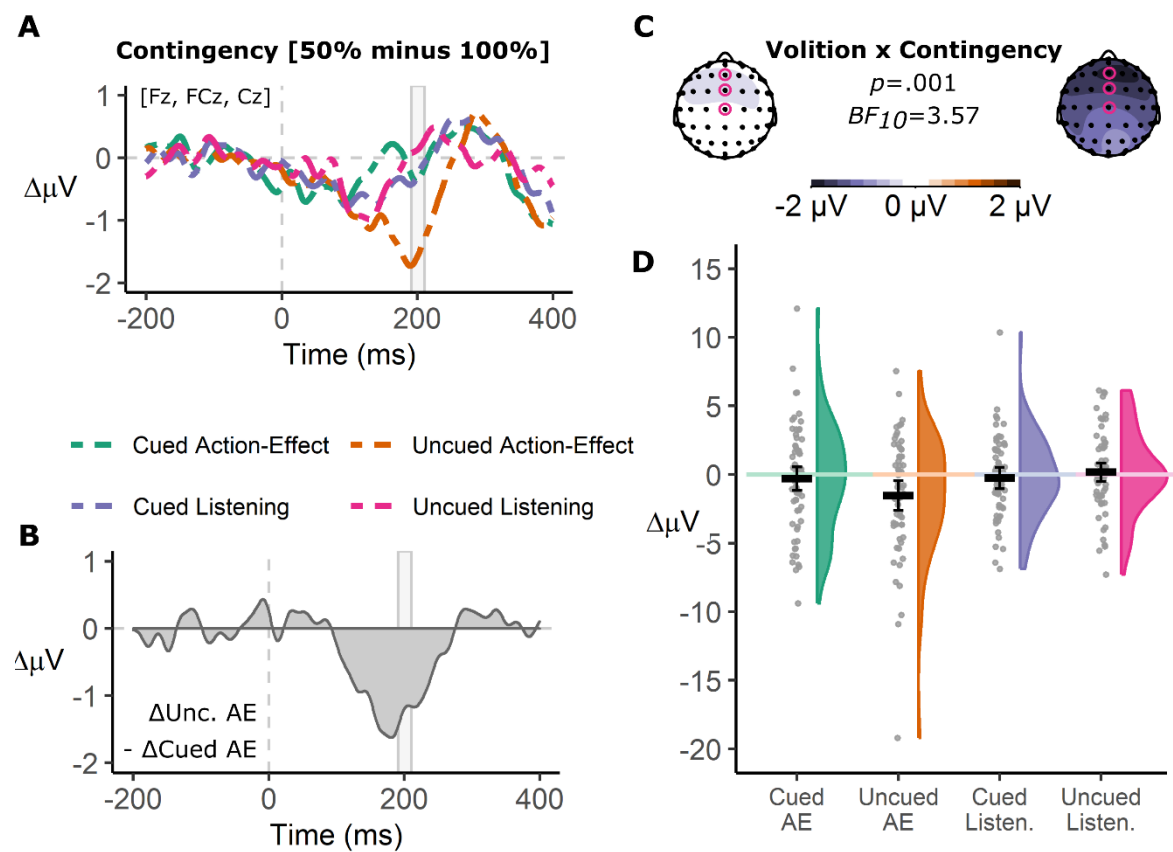
A. Difference waves representing *50%* minus *100%* variants by task condition, including *cued action-effect, uncued action-effect, cued listening* and *uncued listening* condition. **B.** Difference wave, representing contrasts in the effect of *contingency* (i.e., *50%* minus *100%*) between *cued action-effect* and *uncued action-effect* conditions. **C.** Statistical test outcomes relating to the interaction between *volition* and *contingency*. Accompanying topographic maps represent the effect of *contingency* (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 *contingency* (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.

3.2. Behavioural

With regard to behavioural data, consistency in inter-trial interval (ITI) was assessed across experimental conditions based on a 3 x 2 x 2 repeated measures ANOVA. In particular, this investigated differences 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*).

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 exploratory investigation into the influence of stimulus predictability 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 subsequent diminishment of intention-based error monitoring (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 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 *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; Klaffehn et al., 2019; Sowman et al., 2012). In contrast, the effect of *self-generation* was associated with a significant attenuation of P2 amplitudes. This finding is in accordance with other recent studies demonstrating 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.

Our findings 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 predictability 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 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 *contingency* (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 *contingency* 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. However, the non-significant *contingency* x *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 *contingency x volition* interaction (i.e., contrasting the effect of *contingency* in the *uncued action-effect* condition with each of the other conditions) was not significant with respect to effect on N1 amplitudes. These findings are consistent with 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. The *contingency* x *temporal predictability* interaction was also not found to be significant, suggesting that tone frequency prediction did not confer additional suppression to passively observed stimuli when these were made predictable in time. The significant main effect of *contingency* may therefore be consistent with the effects of repetition suppression, whereby a reduction in neural response is observed upon repeated presentation of a 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).

Results pertaining to the N2b extend the work of Le Bars et al. (2019), who demonstrated error monitoring of movement outcomes based on one's intentional production

of motor activity. In particular, we observed a significant interaction between *contingency* 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 *contingency* and *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 appear to reflect error monitoring of movement outcomes when action is 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), error monitoring was not present with respect to the outcomes of stimulus-driven movement when compared with externally-generated stimuli. These results therefore demonstrate error monitoring of action-effects when movement is intentional in terms of *when* action is initiated, similar to effects observed by Le Bars et al. (2019) with respect to agency over *what* motor activity is enacted.

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 an apparent absence of error monitoring with regard to such effects (i.e., N2b amplitudes 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 action-effect predictions may facilitate error monitoring of stimuli that result from volitional movement, reflecting intention-based sensorimotor processes, 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 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). Secondly, clear challenges are present with regard to disentangling the effects associated with ERP components that had overlapping latencies. Difficulty in this regard was most evident in the interpretation of effects associated with *temporal predictability*. 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).

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 error 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 error 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

Sequence	Task	N1		P2		N2b	
		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

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
	Sequence	0.86	51.72	49.24	249.14	11.86	.001	0.17	9.18
	Task	2.94	176.56	62.69	1,291.94	2.91	.036	0.05	1.76
	Sequence x Task	2.59	155.17	0.43	620.21	0.04	.989	0.00	0.02
P2	Intercept	0.74	44.38	1,263.58	1,722.12	44.02	<.001	0.42	1.00
	Sequence	0.77	45.95	15.09	542.04	1.67	.201	0.03	0.23
	Task	2.22	133.15	316.11	2,051.31	9.25	<.001	0.13	334,906.58
	Sequence x Task	2.30	137.84	25.46	774.34	1.97	.120	0.03	0.07
N2b	Intercept	0.82	49.11	231.76	2,488.19	5.59	0.021	0.09	1.00
	Sequence	0.80	47.73	21.04	589.62	2.14	0.149	0.03	0.26
	Task	2.46	147.33	453.50	2,547.14	10.68	0.000	0.15	4,336,194.87
	Sequence x Task	2.39	143.18	79.37	1,010.71	4.71	0.003	0.07	0.42

Table A3

Planned contrasts and interactions

		Est.	*SE*	95% *CI*		*df*	*t*	*p*	*d*	*BF*$_{10}$
				Lower	Upper					
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 Sequence	-0.00	0.10	-0.20	0.19	240	-0.05	.964	-0.01	0.16
	Self-gen. x Sequence	-0.02	0.14	-0.29	0.26	240	-0.13	.896	-0.02	0.17
	Temp. Predict x Sequence	-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 Sequence	-0.22	0.12	-0.46	0.02	240	-1.78	.077	-0.27	0.40
	Self-gen. x Sequence	0.21	0.17	-0.13	0.55	240	1.21	.229	0.16	0.26
	Temp. Predict x Sequence	-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	0.475	-0.11	51.43

Self-gen.	-0.41	0.17	-0.74	-0.08	180	-2.41	0.017	-0.31	1,254.35
Temp. Predict	-0.65	0.29	-1.22	-0.08	180	-2.23	0.027	-0.29	6,692.37
Volition x Sequence	-0.44	0.13	-0.71	-0.18	240	-3.28	0.001	-0.49	3.57
Self-gen. x Sequence	-0.17	0.19	-0.54	0.20	240	-0.88	0.379	-0.11	0.21
Temp. Predict x Sequence	-0.21	0.33	-0.86	0.44	240	-0.63	0.528	-0.08	0.24

Table A4

ITI and Trial Count by Experimental Condition

Auditory Stimuli	Event Activation	Visual Stim.	ITI			Trial Count		
			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