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Establishing intent: Action-effect prediction and error monitoring in volitional control

Author names and affiliations:

Anthony W. Harrison^{1,*} Bruce K. Christensen,² and Thomas J. Whitford¹

¹ *School of Psychology, University of New South Wales, Sydney, Australia*

² *Research School of Psychology, The Australia National University, Canberra, Australia*

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***Corresponding author:**

Anthony W. Harrison, School of Psychology, University of New South Wales,
UNSW Sydney NSW 2052, anthony.harrison@unsw.edu.au.

Abstract:

While volitional movement is thought to be initiated based on its anticipated capacity to achieve sensory goals, stimulus-driven movement may be enacted 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 over movement. 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 the outcomes of stimulus-driven movement are subject to attentional suppression, we propose that this mechanism might also serve to diminish error monitoring of action outcomes. As such, these effects may represent an important feature of sensorimotor processing that differentiates stimuli on the basis of both self-generation and intentionality.

Keywords:

Sensory Attenuation; Internal Forward Models; Prediction; Error Monitoring; 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 thought to support the prioritisation of externally-generated sensations by suppressing the tides of self-generated stimuli associated with an organism’s movement while it navigates through its surrounds (see Crapse & Sommer, 2008). Sensory attenuation is believed to be adaptive because, although representation of externally-generated events relies 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 frameworks suggesting that self-generated sensations are suppressed *based on* the predicted outcomes of movement (Wolpert, 1997). Such accounts include the influential ‘internal forward model’ of motor control (IFM; Miall & Wolpert, 1996; Wolpert et al., 1995). According to the IFM, 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 sensations that result from externally-generated events, 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 system 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) on the basis of motor commands (see Haggard, 2008).

An important distinction has recently been highlighted between action-effects that are closely associated with bodily movements (e.g., proprioceptive and tactile sensations) and more distal outcomes based on interactions with objects in one's environment (e.g., sounds produced by movement; see Dogge, Custers, & Aarts, 2019). Although there is robust evidence in support of suppression based on body-related action-effect predictions (Blakemore et al., 1999; Blakemore et al., 1998, 2000), findings are more equivocal with respect to environment-related associations (Dogge, Custers, & Aarts, 2019). While some research has identified a positive association between action-effect predictability and sensory attenuation in these domains (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, Gayet, 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). The distinction between body- and environment-related action-effects has given rise to alternative accounts of sensory attenuation, including a potential role of sensory gating with respect to body-related movement outcomes (see Press et al., 2023). At the same time, further research is needed to explore discrepant findings with respect to environment-related action effects.

Since its inception in the literature, sensory attenuation of environment-related action-effects 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; Jack et al., 2021; Timm et al., 2014).

Despite a wealth of research exploring sensory attenuation of the N1, several methodological confounds have been identified that challenge the attribution of this phenomenon to distinct processing of self- and externally-generated stimuli (see Hughes et al., 2013). 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 (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 involving the N1 component.

A second methodological confound affecting investigations into sensory attenuation has involved potential differences in physiological arousal and attention (see Horváth, 2015; Hughes et al., 2013). Compared with the passive observation of externally-generated stimuli, tasks that require motor activity to initiate events are likely to involve higher levels of arousal. This possibility may be evidenced by reduced P2 component amplitudes to self- versus externally-generated stimuli (e.g., Bolt & Loehr, 2021, 2023; Harrison et al., 2021), as such effects have been associated with higher states of physiological arousal (e.g., Colrain et al., 2000). It is noteworthy, however, that 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. Similarly, evidence that reduced P2 amplitudes are associated with higher levels of attention may support the notion that self- and externally-generated stimuli are subject to differing levels of attention. 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). This effect represents the influence of ‘top-down’ selective attention, which favours processing of features, object or spatial locations based on task-relevance (see Summerfield & Egner, 2009). 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.

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 the activity of these attentional control processes.

Recent evidence suggests that some forms of self-generated stimuli may be subject to attentional suppression that reduces their resulting N1 amplitudes (Harrison et al., 2023). This form of attentional control involves a reduction in the attraction of ‘bottom-up’ attention to stimuli based on their physical salience (see Summerfield & Egner, 2009). 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 amplitude. 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 stimuli that are produced in time with external cues,

which contributes to an attenuation of resulting N1 amplitudes. The results of a similar experiment suggest that, unlike cued movement, N1 components resulting from stimuli that are produced by uncued movement do not differ in amplitude from those created by externally-generated stimuli that are predictable in time (Harrison et al., 2021). By implicating attentional suppression in sensory attenuation, these findings are consistent with mechanisms proposed by Brown et al. (2013), whereby a reduction in attention serves to decrease the precision weighting of sensory evidence during movement. Further research is needed, however, to explore the functional relevance of these effects, including with respect to action-effect prediction and other aspects of sensorimotor processing.

One promising avenue for exploration involves theorised differences in the use of action-effect prediction in intentional and stimulus-driven movement. Brass and Haggard (2008) identify that intentional movement involves control over *what*, *when* and/or *whether* to act (see also Korka et al., 2022). 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, intentional movement is believed to be guided by its anticipated sensory consequences (Herwig et al., 2007; Pfister et al., 2011) while stimulus-driven movement operates as a form of prepared reflex with less regard for its specific effects (see Hommel, 2000). In addition to experimental findings (Herwig et al., 2007), the distinction between intentional and stimulus-driven movement has been supported by evidence indicating differing neuroanatomical substrates (e.g., Fried et al., 2017; Kriehoff et al., 2011).

Research that has explored differences in the sensorimotor processing of intentional and stimulus-driven movement has demonstrated differing effects of action-effect predictability on N2b component amplitudes (Le Bars et al., 2019). In addition to effects

associated with cognitive load (Bruin & Wijers, 2002; Harrison et al., 2021; Mertens & Polich, 1997), larger N2b amplitudes have been attributed to error monitoring of movement outcomes (Ferdinand et al., 2008; Folstein & Van Petten, 2008). In an experiment by Ferdinand et al. (2008), participants were required to respond to each letter in a sequence with button presses involving different fingers. A repeating sequence was occasionally interrupted by deviant trials, in which the presented letter required a response with an alternate finger. Ferdinand et al. (2008) observed increased N2b amplitudes to self-generated stimuli that deviated from the sequence, with this effect increasing over the course of the experiment. On this basis, Ferdinand et al. (2008) proposed that deviant events were perceived as errors committed by the participant and were reflected in the N2b response. Significantly, 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 stimuli that were produced by movement when the nature of participants' movement was determined by external cues.

Several questions are raised in association with the reviewed literature. Firstly, methodological confounds and discrepancies in previous findings warrant investigation into the influence of action-effect predictability on N1 amplitudes. Given that the sensory attenuation literature has commonly focused on effects involving the N1, and have attributed these to 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 attention may be further explored in the context of these effects. Secondly, research that has demonstrated effects involving action-effect predictability on downstream processing (i.e., N2b amplitudes) has found differences 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 intentional and stimulus-driven movement) or may be attributed to different mechanisms. If N1 effects associated with the temporal cueing of movement are attributable to distinct sensorimotor processing of stimulus-driven and intentional movement, differences in the effects of stimulus predictability may be anticipated in downstream processing. Research is therefore needed to compare the effects of stimulus predictability on N2b components between self-generated stimuli that are produced according to participants' own timing (described henceforth as 'volitional') and those that are externally-generated or result from stimulus-driven movement.

The present study aimed to address these questions by investigating the influence of stimulus predictability on event-related potentials (ERPs) elicited by self- and externally-generated stimuli. 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, trials in the intermixed two-tone variant involved the presentation of a tone frequency with 50% probability. 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). This sample size was constrained by participant and experimenter availability during the academic term. 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 ($M = 0.74$, $SD = 1.17$; see Table S1 in Supplementary Material for details).

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 *one-tone* 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 *two-tone* 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 *one-tone* and *two-tone* 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., one- and two-tone) were the same as those used

in the *uncued motor-auditory* blocks. The allocation of tone frequencies to each condition, and their order within *two-tone* 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., *one-tone* variant) or one of two different frequencies (i.e., *two-tone* variant) in each given trial. Button presses again triggered delivery of a silent audio track to mark events in the *cued motor* condition.

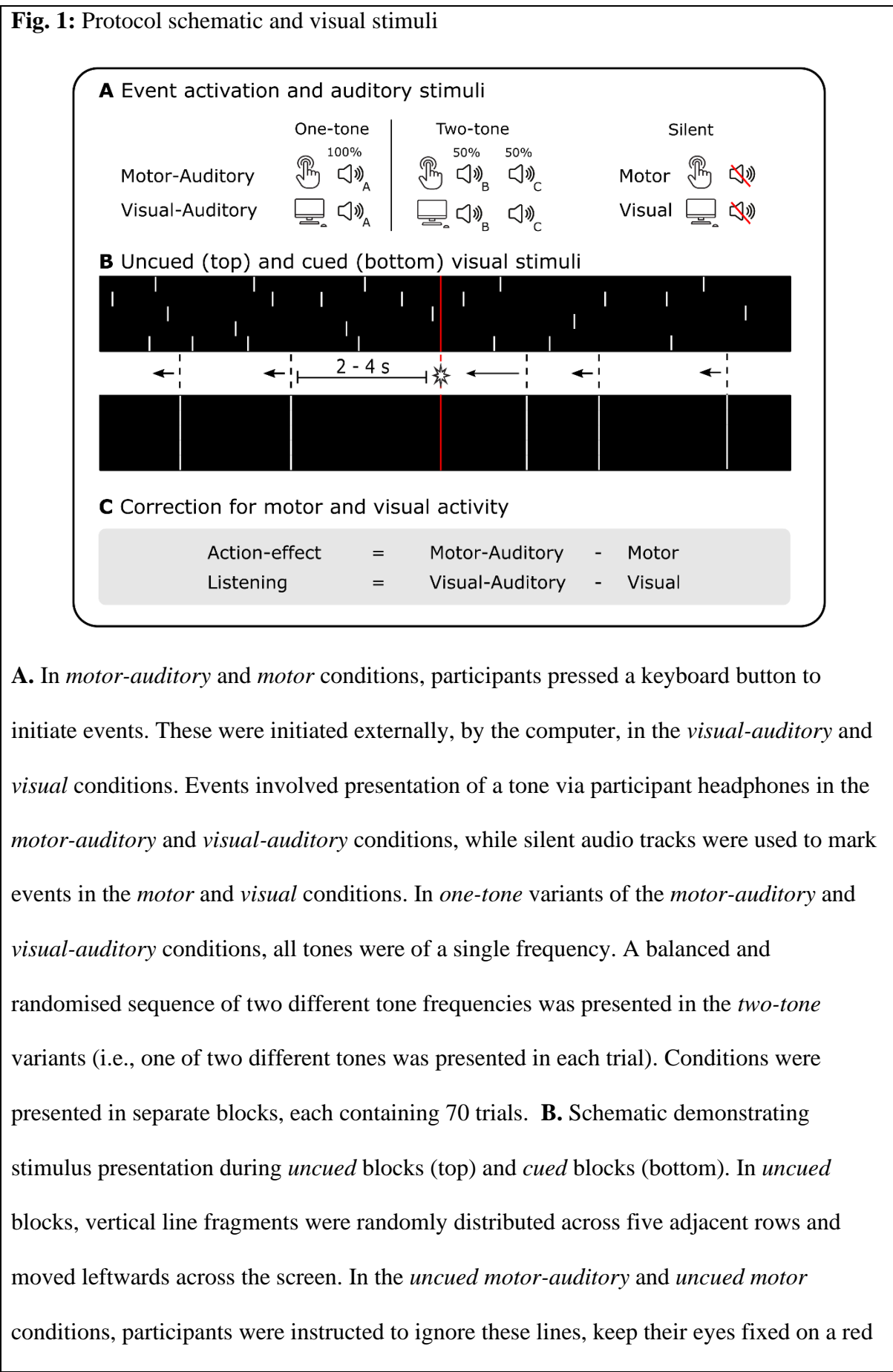
Participants were instructed to passively observe in the *cued visual-auditory* and *cued visual* conditions. In the *cued visual-auditory* condition, tones were presented at the precise moment that each stimulus line intersected with the fixation line. Auditory stimuli were the

same as those described for other conditions, with *one-tone* and *two-tone* 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., one- and two-tone 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.



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 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*.

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 μ V 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 *one-tone* and *two-tone* 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 *two-tone 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 *two-tone 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

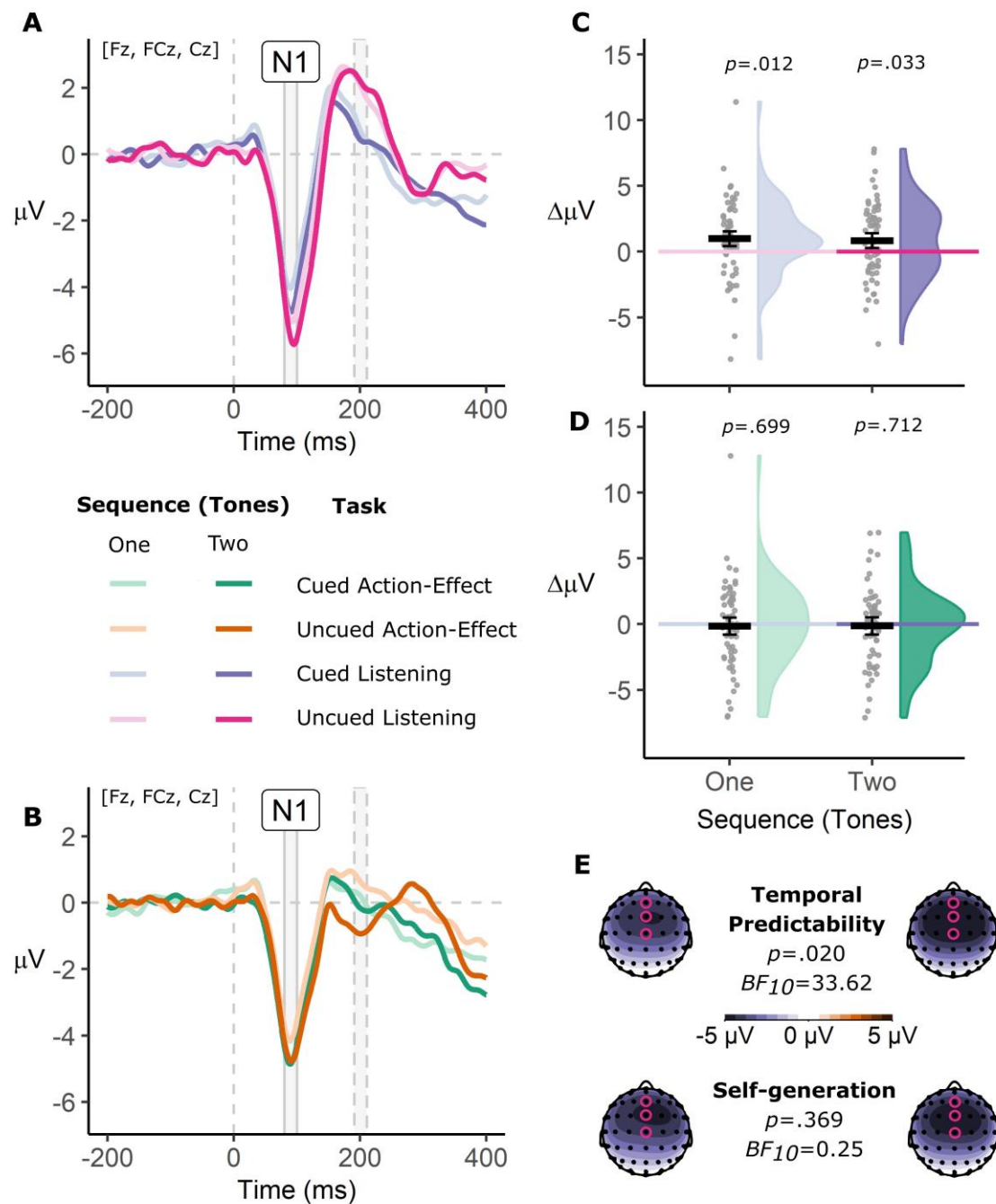
Statistical analyses were based on average recordings, by condition and participant, within 20 ms windows that were centred on each component's peak. Analyses of the N1 involved average recordings between 80 ms and 100 ms post-stimulus, while the P2 was analysed based on those between 151 ms and 171 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 *sequence* (i.e., *one-tone* versus *two-tone*) 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 *sequence* 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). A series of paired-samples Student's t-tests were also conducted to compare component amplitudes of each condition. The results of these t-tests accompany within-subject comparisons in each figure and are reported in detail in the Supplementary Material.

3.1.1. N1

The ANOVA revealed statistically significant main effects of both *sequence*, $F(0.86, 51.72) = 11.86$, $p = .001$, $\eta_p^2 = 0.17$, $BF_{10} = 9.18$, 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 *sequence* and each of the planned comparisons. This included the *temporal predictability* x *sequence* interaction, $t(240) = -0.32$, $p = .751$, $d = -0.04$, $BF_{10} = 0.11$, and the *self-generation* x *sequence* 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).

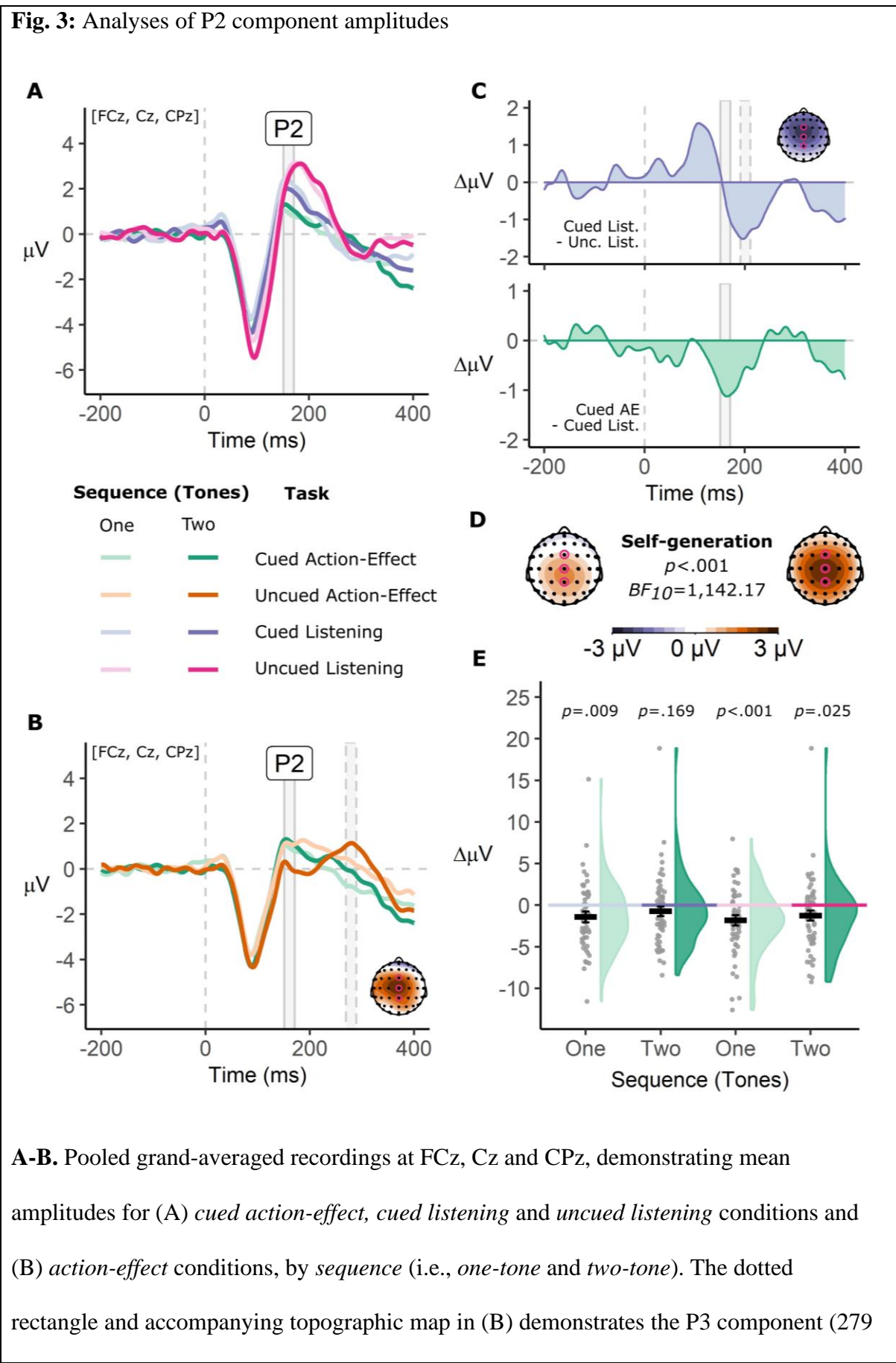
Fig. 2: Analyses of N1 component amplitudes

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 *sequence* (i.e., *one-tone* and *two-tone*). 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 *sequence* (i.e., *one-tone* and *two-tone*). Error bars represent 95% confidence intervals and *p*-values report the results of paired-samples Student's *t*-tests. **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 *sequence*, $F(0.77, 45.95) = 1.67, p = .201, \eta_p^2 = 0.03, BF_{10} = 0.23$, and the interaction between *task* and *sequence*, $F(2.30, 137.84) = 1.97, p = .120, \eta_p^2 = 0.03, BF_{10} = 0.07$. 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 *sequence*, were not found to be statistically significant (see Table A3).



ms post-stimulus) in the *two-tone 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 *one-* and *two-tone* 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 *sequence* (i.e., *one-tone* and *two-tone*). Error bars represent 95% confidence and *p*-values report the results of paired-samples Student's *t*-tests.

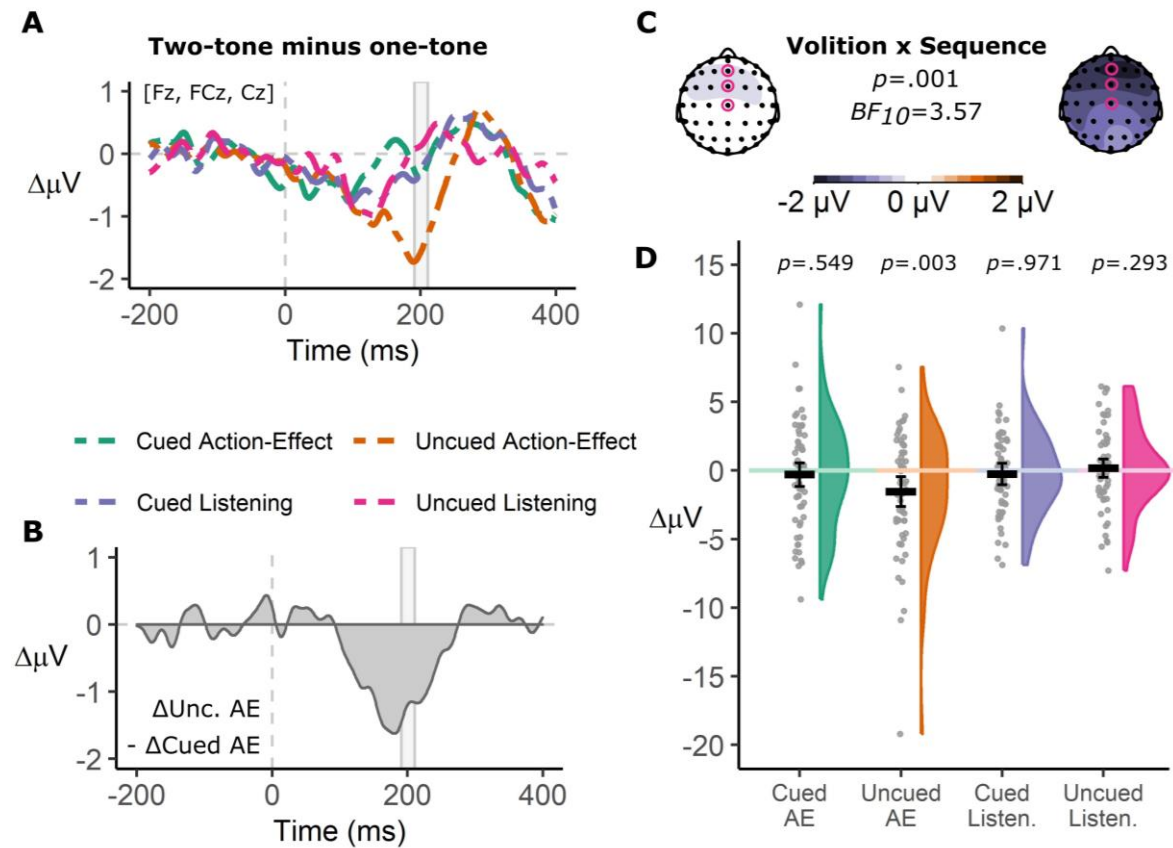
3.1.3. N2b

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 *sequence* and *task*, as well as their interaction. To reiterate, the effect of *sequence* compared the response evoked by tones in blocks containing *one-* and *two-tone* sequences. 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 sequence 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 *sequence*, $F(2.39, 143.18) = 4.71, p = .003, \eta_p^2 = 0.07, BF_{10} = 0.42$. 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 predictability 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 *sequence* (i.e., *one-* versus *two-tone*).

Importantly, a significant interaction was observed between *volition* and *sequence*, $t(240) = -3.28, p = 0.001, d = -0.49, BF_{10} = 3.57$. This interaction was such that the *two-tone* sequence resulted in larger N2b amplitudes than the *one-tone* sequence 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 *two-tone* minus *one-tone* 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 sequence (i.e., *two-tone* minus *one-tone*) between *cued action-effect* and *uncued action-effect* conditions. **C.** Statistical test outcomes relating to the interaction between *volition* and *sequence*. Accompanying topographic maps represent the effect of *sequence* (i.e., *two-tone* minus *one-tone*) 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 *sequence* (i.e., *two-tone* minus *one-tone*) for each *task* condition, including *cued action-effect*, *uncued action-effect*, *cued listening* and

uncued listening. Error bars represent 95% confidence intervals and p -values report the results of paired-samples Student's t -tests.

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., *one-tone*, *two-tone* 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.

4. Discussion

In the present study, we investigated several questions relating to the influence of stimulus predictability on ERPs elicited by self- and externally-generated stimuli. The experiment was designed to facilitate an assessment of sensory attenuation involving the N1 component in a manner that explored effects associated with attention and temporal predictability. We also sought to assess a potential relationship between the attentional suppression of outcomes to stimulus-driven movement (Harrison et al., 2023) and subsequent

diminishment of intention-based processing of action-effects. 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 more robust effect of self-generation on P2 amplitudes (e.g., Bolt & Loehr, 2021, 2023; Harrison et al., 2021). As a reduction in P2 amplitudes has been attributed to activity involving the termination of selective attention, these findings may reflect disengagement of implicit attention to self-generated stimuli. Further research is needed to explore this possibility.

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. According to standard conventions (Cohen, 1988, 1992), the effect size contrasting similar conditions in Harrison et al. (2021) was medium (i.e., $d = 0.62$ and $d = 0.55$) and in Harrison et al. (2023) this was medium-large (i.e., $\eta_p^2 = 0.133$).

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 *sequence* (i.e., contrasting *one-tone* and *two-tone* variants of each condition) are informative to understanding the influence of stimulus and action-effect predictability on sensory processing. The effect of *sequence* 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 *sequence* 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 *sequence x volition* interaction (i.e., contrasting the effect of *sequence* 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 *sequence 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 *sequence* 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 provide a conceptual replication and 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 *sequence* 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 *two-tone* variant of the *uncued action-effect* condition compared with the *one-tone* 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 *sequence* 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.

Our findings are consistent with the auditory event representation system (AERS), proposed by Winkler and Schröger (2015), and its extension by Korka et al. (2022) to account for the processing of action-effects that are associated with intentional movement. Importantly, the extended AERS (Korka et al., 2022) provides a computational framework that distinguishes between effects associated with regularity-based prediction (e.g., cross-modal sensory and simple action-effect associations) and those of intention-based prediction (i.e., associated with one's sensory objectives during movement). The extended AERS posits a process whereby regularity-based predictions within a sensory predictive model are assessed prior to intention-based predictions. This is supported by research demonstrating that N1 amplitudes are modulated by regularity-based prediction and not intention-based prediction (Korka et al., 2019). In contrast, intention-based prediction has been found to engage higher-order deviance detection in downstream processing (Korka et al., 2021; Widmann & Schröger, 2022). Our results provide a conceptual replication of these findings, demonstrating that intentional action-effects (i.e., those in the *uncued action-effect* condition) do not affect N1 amplitudes but are instead evaluated downstream, as evidenced by their influence on the N2b component.

In conjunction with previous findings, our results may provide insight into the manner by which intention-based action-effects are distinguished from other events within the AERS sensory predictive model (i.e., to facilitate subsequent intention-based evaluation). 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 solely on one's intentions from those that are produced in response to external stimuli and ambiguous with respect to self-generation.

By providing further evidence that intention-based error monitoring occurs downstream, rather than influencing the primary cortical response, our findings may also serve to address challenges associated with the perceptual prediction paradox (see Press et al., 2020). This paradox involves potentially conflicting theories with respect to the use of prediction in shaping a perceptual experience that is both informative and veridical. On the one hand, predictions are believed to bias perception towards more likely interpretations of sensory material. On the other, predicted stimuli are believed to be suppressed so as to

prioritise the detection of unexpected events. While the use of action-effect prediction to suppress primary cortical activity may be adaptive in facilitating informative perceptual experiences (i.e., the detection of unpredicted outcomes to movement), this may be incompatible with the use of probabilistic information to shape a veridical perception of self-generated events. The opposing process theory, proposed by Press et al. (2020), suggests that perception is first biased towards likely interpretations (i.e., based on prior expectations) and that prediction violations are upweighted in subsequent processing. While further research is needed, this notion may be consistent with growing evidence that the N1 is not influenced by action-effect predictability (Bednark et al., 2015; Dogge, Hofman, et al., 2019; Harrison et al., 2023) and that associated prediction errors are instead reflected in downstream processing (Korka et al., 2021; Widmann & Schröger, 2022).

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).

Finally, there were limitations with respect to the fixation stimulus and other visual stimuli used in the experiment. While these stimuli were similar to those of prior studies (Harrison et al., 2023; Harrison et al., 2021), it is noteworthy that the absence of a vertical reference point on the fixation line meant that participants' eye movements were not controlled in this regard and may have affected the data quality. Similarly, movement of stimulus lines (i.e., in *cued* conditions) and line fragments (i.e., in *uncued* conditions) past the fixation line may have disrupted participants' visual gaze. Future research may better control for such effects through more advanced artefact correction techniques, including independent components analysis. In addition, despite participants being instructed not to base their button press on line fragments in the *uncued motor* and *uncued motor-auditory* conditions, this possibility could not be ruled out. Nevertheless, significant differences between the *uncued action-effect* and other conditions reflect an adequate level of adherence to task instructions.

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 are not involved in sensory attenuation of the N1 component, 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 more 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 the presented findings may warrant reconsideration of theoretical accounts used to explain sensory attenuation, and other

putative mechanisms of the IFM, they provide promising new avenues for investigation of sensorimotor processing.

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7. 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.

8. Data Availability Statement

Data and scripts used in the present investigation are available and can be accessed at https://osf.io/ecy32/?view_only=db32ddcf13d645cc97bf6086569e37af. This is a temporary view-only link that will be replaced with a permanent link upon publication.

9. Notes

No part of the study procedures or analyses was preregistered prior to the research being conducted. We report how we determined our sample size, all data exclusions, all

inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

10. Competing Interests

The authors have no competing interests to declare.

11. References

- Aliu, S. O., Houde, J. F., & Nagarajan, S. S. (2009). Motor-induced Suppression of the Auditory Cortex. *Journal of Cognitive Neuroscience*, 21(4), 791-802. <https://doi.org/10.1162/jocn.2009.21055>
- Baess, P., Horváth, J., Jacobsen, T., & Schröger, E. (2011). Selective suppression of self-initiated sounds in an auditory stream: An ERP study. *Psychophysiology*, 48(9), 1276-1283. <https://doi.org/10.1111/j.1469-8986.2011.01196.x>
- Baess, P., Jacobsen, T., & Schröger, E. (2008). Suppression of the auditory N1 event-related potential component with unpredictable self-initiated tones: Evidence for internal forward models with dynamic stimulation. *International Journal of Psychophysiology*, 70(2), 137-143. <https://doi.org/10.1016/j.ijpsycho.2008.06.005>
- Bednark, J. G., Poonian, S. K., Palghat, K., McFadyen, J., & Cunnington, R. (2015). Identity-specific predictions and implicit measures of agency. *Psychology of Consciousness: Theory, Research, and Practice*, 2, 253-268. <https://doi.org/10.1037/cns0000062>
- Blakemore, S.-J., Frith, C. D., & Wolpert, D. M. (1999). Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience*, 11(5), 551-559. <https://doi.org/10.1162/089892999563607>
- Blakemore, S.-J., Wolpert, D., & Frith, C. (1998). Central cancellation of self-produced tickle sensation. *Nature Neuroscience*, 1, 635. <https://doi.org/10.1038/2870>

Blakemore, S.-J., Wolpert, D., & Frith, C. (2000). Why can't you tickle yourself?

NeuroReport, 11(11), R11-R16. <https://doi.org/10.4324/9781351197670-4>

Bolt, N. K., & Loehr, J. D. (2021). Sensory Attenuation of the Auditory P2 Differentiates

Self- from Partner-Produced Sounds during Joint Action. *Journal of Cognitive*

Neuroscience, 33(11), 2297-2310. https://doi.org/10.1162/jocn_a_01760

Bolt, N. K., & Loehr, J. D. (2023). The auditory P2 differentiates self- from partner-produced

sounds during joint action: Contributions of self-specific attenuation and temporal orienting of attention. *Neuropsychologia*, 182, 108526.

<https://doi.org/10.1016/j.neuropsychologia.2023.108526>

Brass, M., & Haggard, P. (2008). The What, When, Whether Model of Intentional Action.

The Neuroscientist, 14(4), 319-325. <https://doi.org/10.1177/1073858408317417>

Brown, H., Adams, R. A., Parees, I., Edwards, M., & Friston, K. (2013). Active inference,

sensory attenuation and illusions. *Cognitive Processing*, 14(4), 411-427.

<https://doi.org/10.1007/s10339-013-0571-3>

Bruin, K. J., & Wijers, A. A. (2002). Inhibition, response mode, and stimulus probability: a

comparative event-related potential study. *Clinical Neurophysiology*, 113(7), 1172-

1182. [https://doi.org/10.1016/S1388-2457\(02\)00141-4](https://doi.org/10.1016/S1388-2457(02)00141-4)

Cao, L., Veniero, D., Thut, G., & Gross, J. (2017). Role of the Cerebellum in Adaptation to

Delayed Action Effects. *Curr Biol*, 27(16), 2442-2451.e2443.

<https://doi.org/10.1016/j.cub.2017.06.074>

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2 ed.). Lawrence

Earlbaum Associates.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, 112(1), 155.

<https://doi.org/10.1037/0033-2909.112.1.155>

- Colrain, I. M., Di Parsia, P., & Gora, J. (2000). The impact of prestimulus EEG frequency on auditory evoked potentials during sleep onset. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, 54(4), 243. <https://doi.org/10.1037/h0087344>
- Coull, J. T. (1998). Neural correlates of attention and arousal: insights from electrophysiology, functional neuroimaging and psychopharmacology. *Progress in Neurobiology*, 55(4), 343-361. [https://doi.org/10.1016/S0301-0082\(98\)00011-2](https://doi.org/10.1016/S0301-0082(98)00011-2)
- Crapse, T. B., & Sommer, M. A. (2008). Corollary discharge across the animal kingdom. *Nature Reviews Neuroscience*, 9(8), 587-600. <https://doi.org/10.1038/nrn2457>
- Crowley, K., & Colrain, I. M. (2004). A review of the evidence for P2 being an independent component process: age, sleep and modality. *Clinical Neurophysiology*, 115(4), 732-744. <https://doi.org/10.1016/j.clinph.2003.11.021>
- Darriba, Á., Hsu, Y.-F., Van Ommen, S., & Waszak, F. (2021). Intention-based and sensory-based predictions. *Scientific Reports*, 11(1), 19899. <https://doi.org/10.1038/s41598-021-99445-z>
- Desimone, R. (1996). Neural Mechanisms for Visual Memory and their Role in Attention. *Proceedings of the National Academy of Sciences of the United States of America*, 93(24), 13494-13499. <https://doi.org/10.1073/pnas.93.24.13494>
- Dogge, M., Custers, R., & Aarts, H. (2019). Moving Forward: On the Limits of Motor-Based Forward Models. *Trends in Cognitive Sciences*, 23(9), 743-753. <https://doi.org/10.1016/j.tics.2019.06.008>
- Dogge, M., Custers, R., Gayet, S., Hoijsink, H., & Aarts, H. (2019). Perception of action-outcomes is shaped by life-long and contextual expectations. *Scientific Reports*, 9(1), 5225. <https://doi.org/10.1038/s41598-019-41090-8>

- Dogge, M., Hofman, D., Custers, R., & Aarts, H. (2019). Exploring the role of motor and non-motor predictive mechanisms in sensory attenuation: Perceptual and neurophysiological findings. *Neuropsychologia*, 124, 216-225.
<https://doi.org/10.1016/j.neuropsychologia.2018.12.007>
- Egan, S., Ghio, M., & Bellebaum, C. (2023). Auditory N1 and P2 Attenuation in Action Observation: An Event-Related Potential Study Considering Effects of Temporal Predictability and Individualism. *Biological Psychology*, 108575.
<https://doi.org/10.1016/j.biopsycho.2023.108575>
- Ferdinand, N. K., Mecklinger, A., & Kray, J. (2008). Error and Deviance Processing in Implicit and Explicit Sequence Learning. *Journal of Cognitive Neuroscience*, 20(4), 629-642. <https://doi.org/10.1162/jocn.2008.20046>
- Field, A., Miles, J., & Field, Z. (2012). *Discovering statistics using R*. SAGE.
- Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: A review. *Psychophysiology*, 45(1), 152-170.
<https://doi.org/10.1111/j.1469-8986.2007.00602.x>
- Ford, J. M., Palzes, V. A., Roach, B. J., & Mathalon, D. H. (2014). Did I Do That? Abnormal Predictive Processes in Schizophrenia When Button Pressing to Deliver a Tone. *Schizophrenia Bulletin*, 40(4), 804-812. <https://doi.org/10.1093/schbul/sbt072>
- Fried, I., Haggard, P., He, B. J., & Schurger, A. (2017). Volition and Action in the Human Brain: Processes, Pathologies, and Reasons. *The Journal of Neuroscience*, 37(45), 10842. <https://doi.org/10.1523/JNEUROSCI.2584-17.2017>
- Friston, K. (2009). The free-energy principle: a rough guide to the brain? *Trends in Cognitive Sciences*, 13(7), 293-301. <https://doi.org/10.1016/j.tics.2009.04.005>

- Friston, K., Daunizeau, J., Kilner, J., & Kiebel, S. J. (2010). Action and behavior: a free-energy formulation. *Biological Cybernetics*, 102(3), 227-260.
<https://doi.org/10.1007/s00422-010-0364-z>
- García-Larrea, L., Lukaszewicz, A.-C., & Mauguière, F. (1992). Revisiting the oddball paradigm. Non-target vs neutral stimuli and the evaluation of ERP attentional effects. *Neuropsychologia*, 30(8), 723-741. [https://doi.org/10.1016/0028-3932\(92\)90042-K](https://doi.org/10.1016/0028-3932(92)90042-K)
- Geisser, S., & Greenhouse, S. W. (1958). An Extension of Box's Results on the Use of the F Distribution in Multivariate Analysis. *Ann. Math. Statist.*, 29(3), 885-891.
<https://doi.org/10.1214/aoms/1177706545>
- Gelman, A., Jakulin, A., Pittau, M. G., & Su, Y.-S. (2008). A weakly informative default prior distribution for logistic and other regression models. *Ann. Appl. Stat.*, 2(4), 1360-1383. <https://doi.org/10.1214/08-AOAS191>
- Giard, M. H., Perrin, F., Echallier, J. F., Thévenet, M., Froment, J. C., & Pernier, J. (1994). Dissociation of temporal and frontal components in the human auditory N1 wave: a scalp current density and dipole model analysis. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, 92(3), 238-252.
[https://doi.org/10.1016/0168-5597\(94\)90067-1](https://doi.org/10.1016/0168-5597(94)90067-1)
- Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, 55(4), 468-484. [https://doi.org/10.1016/0013-4694\(83\)90135-9](https://doi.org/10.1016/0013-4694(83)90135-9)
- Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: neural models of stimulus-specific effects. *Trends in Cognitive Sciences*, 10(1), 14-23.
<https://doi.org/10.1016/j.tics.2005.11.006>
- Guo, J., & Song, J. H. (2019). Action Fluency Facilitates Perceptual Discrimination. *Psychol Sci*, 30(10), 1434-1448. <https://doi.org/10.1177/0956797619859361>

- Haggard, P. (2008). Human volition: towards a neuroscience of will. *Nature Reviews Neuroscience*, 9(12), 934-946. <https://doi.org/10.1038/nrn2497>
- Harrison, A. W., Hughes, G., Rudman, G., Christensen, B. K., & Whitford, T. J. (2023). Exploring the internal forward model: Action-effect prediction and attention in sensorimotor processing. *Cerebral Cortex*. <https://doi.org/10.1093/cercor/bhad189>
- Harrison, A. W., Mannion, D. J., Jack, B. N., Griffiths, O., Hughes, G., & Whitford, T. J. (2021). Sensory attenuation is modulated by the contrasting effects of predictability and control. *NeuroImage*, 237, 118103. <https://doi.org/10.1016/j.neuroimage.2021.118103>
- Herwig, A., Prinz, W., & Waszak, F. (2007). Two Modes of Sensorimotor Integration in Intention-Based and Stimulus-Based Actions. *Quarterly Journal of Experimental Psychology*, 60(11), 1540-1554. <https://doi.org/10.1080/17470210601119134>
- Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical Signs of Selective Attention in the Human Brain. *Science*, 182(4108), 177. <https://doi.org/10.1126/science.182.4108.177>
- Hommel, B. (2000). The Prepared Reflex: Automaticity and Control in Stimulus-Response Translation. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 247-273). MIT Press.
- Horváth, J. (2015). Action-related auditory ERP attenuation: Paradigms and hypotheses. *Brain Research*, 1626, 54-65. <https://doi.org/10.1016/j.brainres.2015.03.038>
- Huang, J., Hensch, T., Ulke, C., Sander, C., Spada, J., Jawinski, P., & Hegerl, U. (2017). Evoked potentials and behavioral performance during different states of brain arousal. *BMC Neuroscience*, 18(1), 21. <https://doi.org/10.1186/s12868-017-0340-9>
- Hughes, G., Desantis, A., & Waszak, F. (2013). Mechanisms of intentional binding and sensory attenuation: The role of temporal prediction, temporal control, identity

prediction, and motor prediction. *Psychological Bulletin*, 139(1), 133-151.

<https://doi.org/10.1037/a0028566>

Jack, B. N., Chilver, M. R., Vickery, R. M., Birnieks, I., Krstanoska-Blazeska, K., Whitford, T. J., & Griffiths, O. (2021). Movement Planning Determines Sensory Suppression: An Event-related Potential Study. *Journal of Cognitive Neuroscience*, 33(12), 2427-2439. https://doi.org/10.1162/jocn_a_01747

James, W. (1890). *The principles of psychology*. Dover Publications.

Jeffreys, H. (1998). *Theory of probability* (3 ed.). Clarendon Press.

Kaiser, J., & Schütz-Bosbach, S. (2018). Sensory attenuation of self-produced signals does not rely on self-specific motor predictions. *European Journal of Neuroscience*, 47(11), 1303-1310. <https://doi.org/10.1111/ejn.13931>

Klaffehn, A. L., Baess, P., Kunde, W., & Pfister, R. (2019). Sensory attenuation prevails when controlling for temporal predictability of self- and externally generated tones. *Neuropsychologia*, 132, 107145. <https://doi.org/10.1016/j.neuropsychologia.2019.107145>

Kok, P., Rahnev, D., Jehee, J. F. M., Lau, H. C., & de Lange, F. P. (2012). Attention Reverses the Effect of Prediction in Silencing Sensory Signals. *Cerebral Cortex*, 22(9), 2197-2206. <https://doi.org/10.1093/cercor/bhr310>

Korka, B., Schröger, E., & Widmann, A. (2019). Action Intention-based and Stimulus Regularity-based Predictions: Same or Different? *Journal of Cognitive Neuroscience*, 31(12), 1917-1932. https://doi.org/10.1162/jocn_a_01456

Korka, B., Schröger, E., & Widmann, A. (2021). The encoding of stochastic regularities is facilitated by action-effect predictions. *Scientific Reports*, 11(1), 6790. <https://doi.org/10.1038/s41598-021-86095-4>

- Korka, B., Widmann, A., Waszak, F., Darriba, Á., & Schröger, E. (2022). The auditory brain in action: Intention determines predictive processing in the auditory system—A review of current paradigms and findings. *Psychonomic Bulletin & Review*, 29(2), 321-342. <https://doi.org/10.3758/s13423-021-01992-z>
- Krieghoff, V., Waszak, F., Prinz, W., & Brass, M. (2011). Neural and behavioral correlates of intentional actions. *Neuropsychologia*, 49(5), 767-776. <https://doi.org/10.1016/j.neuropsychologia.2011.01.025>
- Lange, K. (2009). Brain correlates of early auditory processing are attenuated by expectations for time and pitch. *Brain and Cognition*, 69(1), 127-137. <https://doi.org/10.1016/j.bandc.2008.06.004>
- Lange, K. (2011). The reduced N1 to self-generated tones: An effect of temporal predictability? *Psychophysiology*, 48(8), 1088-1095. <https://doi.org/10.1111/j.1469-8986.2010.01174.x>
- Le Bars, S., Darriba, Á., & Waszak, F. (2019). Event-related brain potentials to self-triggered tones: Impact of action type and impulsivity traits. *Neuropsychologia*, 125, 14-22. <https://doi.org/10.1016/j.neuropsychologia.2019.01.012>
- Luck, S. J., & Gaspelin, N. (2017). How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology*, 54(1), 146-157. <https://doi.org/10.1111/psyp.12639>
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, 164(1), 177-190. <https://doi.org/10.1016/j.jneumeth.2007.03.024>
- Martikainen, M. H., Kaneko, K.-i., & Hari, R. (2005). Suppressed Responses to Self-triggered Sounds in the Human Auditory Cortex. *Cerebral Cortex*, 15(3), 299-302. <https://doi.org/10.1093/cercor/bhh131>

Mauchly, J. W. (1940). Significance Test for Sphericity of a Normal n-Variate Distribution.

The Annals of Mathematical Statistics, 11(2), 204-209.

<https://doi.org/10.1214/aoms/1177731915>

Mertens, R., & Polich, J. (1997). P300 from a single-stimulus paradigm: passive versus active tasks and stimulus modality. *Electroencephalography and Clinical*

Neurophysiology/Evoked Potentials Section, 104(6), 488-497.

[https://doi.org/10.1016/S0168-5597\(97\)00041-5](https://doi.org/10.1016/S0168-5597(97)00041-5)

Miall, R. C., & Wolpert, D. M. (1996). Forward Models for Physiological Motor Control.

Neural Networks, 9(8), 1265-1279. [https://doi.org/10.1016/S0893-6080\(96\)00035-4](https://doi.org/10.1016/S0893-6080(96)00035-4)

Mifsud, N. G., Beesley, T., Watson, T. L., & Whitford, T. J. (2016). Attenuation of auditory evoked potentials for hand and eye-initiated sounds. *Biological Psychology*, 120, 61-

68. <https://doi.org/10.1016/j.biopsycho.2016.08.011>

Mifsud, N. G., & Whitford, T. J. (2017). Sensory attenuation of self-initiated sounds maps onto habitual associations between motor action and sound. *Neuropsychologia*, 103,

38-43. <https://doi.org/10.1016/j.neuropsychologia.2017.07.019>

Miller, G. A., Gratton, G., & Yee, C. M. (1988). Generalized implementation of an eye movement correction procedure. *Psychophysiology*, 25(2), 241-243.

<https://doi.org/10.1111/j.1469-8986.1988.tb00999.x>

Morey, R., & Rouder, J. (2018). *BayesFactor 0.9. 12-2*. In *Comprehensive R Archive*

Network <http://cran.rproject.org/web/packages/BayesFactor/index.html>

Mulert, C., Jäger, L., Propp, S., Karch, S., Störmann, S., Pogarell, O., Möller, H.-J., Juckel,

G., & Hegerl, U. (2005). Sound level dependence of the primary auditory cortex:

Simultaneous measurement with 61-channel EEG and fMRI. *NeuroImage*, 28(1), 49-

58. <https://doi.org/10.1016/j.neuroimage.2005.05.041>

Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42(4), 313-329.

[https://doi.org/10.1016/0001-6918\(78\)90006-9](https://doi.org/10.1016/0001-6918(78)90006-9)

Näätänen, R., & Picton, T. (1987). The N1 Wave of the Human Electric and Magnetic Response to Sound: A Review and an Analysis of the Component Structure.

Psychophysiology, 24(4), 375-425. [https://doi.org/10.1111/j.1469-](https://doi.org/10.1111/j.1469-8986.1987.tb00311.x)

[8986.1987.tb00311.x](https://doi.org/10.1111/j.1469-8986.1987.tb00311.x)

Neszmélyi, B., & Horváth, J. (2017). Consequences matter: Self-induced tones are used as feedback to optimize tone-eliciting actions. *Psychophysiology*, 54(6), 904-915.

<https://doi.org/10.1111/psyp.12845>

Neumann, O. (1984). Automatic processing: A review of recent findings and a plea for an old theory. In W. Prinz & A. Sanders (Eds.), *Cognition and motor processes* (pp. 255-

293). Springer-Verlag. https://doi.org/10.1007/978-3-642-69382-3_17

Novak, G., Ritter, W., & Vaughan Jr, H. G. (1992). Mismatch Detection and the Latency of Temporal Judgments. *Psychophysiology*, 29(4), 398-411.

<https://doi.org/10.1111/j.1469-8986.1992.tb01713.x>

Oestreich, L. K. L., Mifsud, N. G., Ford, J. M., Roach, B. J., Mathalon, D. H., & Whitford, T.

J. (2015). Subnormal sensory attenuation to self-generated speech in schizotypy:

Electrophysiological evidence for a ‘continuum of psychosis’. *International Journal*

of Psychophysiology, 97(2), 131-138. <https://doi.org/10.1016/j.ijpsycho.2015.05.014>

Pfister, R., Kiesel, A., & Hoffmann, J. (2011). Learning at any rate: Action–effect learning for stimulus-based actions. *Psychological Research*, 75(1), 61-65.

<https://doi.org/10.1007/s00426-010-0288-1>

Press, C., Kok, P., & Yon, D. (2020). The Perceptual Prediction Paradox. *Trends in Cognitive*

Sciences, 24(1), 13-24. <https://doi.org/10.1016/j.tics.2019.11.003>

- Press, C., Thomas, E. R., & Yon, D. (2023). Cancelling cancellation? Sensorimotor control, agency, and prediction. *Neuroscience & Biobehavioral Reviews*, 145, 105012. <https://doi.org/10.1016/j.neubiorev.2022.105012>
- Pritchard, W. S., Shappell, S. A., & Brandt, M. E. (1991). Psychophysiology of N200/N400: A review and classification scheme. *Advances in psychophysiology*, 4, 43-106. <https://doi.org/10.1111/psyp.1201x>
- Reznik, D., Guttman, N., Buaron, B., Zion-Golumbic, E., & Mukamel, R. (2021). Action-locked Neural Responses in Auditory Cortex to Self-generated Sounds. *Cerebral Cortex*, 31(12), 5560-5569. <https://doi.org/10.1093/cercor/bhab179>
- Reznik, D., Henkin, Y., Levy, O., & Mukamel, R. (2015). Perceived Loudness of Self-Generated Sounds Is Differentially Modified by Expected Sound Intensity. *PLOS ONE*, 10(5), e0127651. <https://doi.org/10.1371/journal.pone.0127651>
- Reznik, D., Henkin, Y., Schadel, N., & Mukamel, R. (2014). Lateralized enhancement of auditory cortex activity and increased sensitivity to self-generated sounds. *Nature Communications*, 5(1), 4059. <https://doi.org/10.1038/ncomms5059>
- Sanmiguel, I., Todd, J., & Schröger, E. (2013). Sensory suppression effects to self-initiated sounds reflect the attenuation of the unspecific N1 component of the auditory ERP. *Psychophysiology*, 50(4), 334-343. <https://doi.org/10.1111/psyp.12024>
- Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A Common Neural Mechanism for Preventing and Terminating the Allocation of Attention. *The Journal of Neuroscience*, 32(31), 10725. <https://doi.org/10.1523/JNEUROSCI.1864-12.2012>
- Sawaki, R., & Luck, S. J. (2013). Active suppression after involuntary capture of attention. *Psychonomic Bulletin & Review*, 20(2), 296-301. <https://doi.org/10.3758/s13423-012-0353-4>

- Schafer, E. W. P., & Marcus, M. M. (1973). Self-Stimulation Alters Human Sensory Brain Responses. *Science*, 181(4095), 175. <https://doi.org/10.1126/science.181.4095.175>
- Schröger, E., Marzecová, A., & SanMiguel, I. (2015). Attention and prediction in human audition: a lesson from cognitive psychophysiology. *European Journal of Neuroscience*, 41(5), 641-664. <https://doi.org/10.1111/ejn.12816>
- Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin*, 136(6), 943-974. <https://doi.org/10.1037/a0020541>
- Sowman, P. F., Kuusik, A., & Johnson, B. W. (2012). Self-initiation and temporal cueing of monaural tones reduce the auditory N1 and P2. *Experimental Brain Research*, 222(1), 149-157. <https://doi.org/10.1007/s00221-012-3204-7>
- Sperry, R. W. (1950). Neural basis of the spontaneous optokinetic response produced by visual inversion. *Journal of Comparative and Physiological Psychology*, 43(6), 482-489. <https://doi.org/10.1037/h0055479>
- Summerfield, C., & Egner, T. (2009). Expectation (and attention) in visual cognition. *Trends in Cognitive Sciences*, 13(9), 403-409. <https://doi.org/10.1016/j.tics.2009.06.003>
- Thomas, E. R., Yon, D., de Lange, F. P., & Press, C. (2022). Action Enhances Predicted Touch. *Psychol Sci*, 33(1), 48-59. <https://doi.org/10.1177/09567976211017505>
- Timm, J., SanMiguel, I., Keil, J., Schröger, E., & Schönwiesner, M. (2014). Motor Intention Determines Sensory Attenuation of Brain Responses to Self-initiated Sounds. *Journal of Cognitive Neuroscience*, 26(7), 1481-1489. https://doi.org/10.1162/jocn_a_00552
- Timm, J., Schönwiesner, M., Schröger, E., & SanMiguel, I. (2016). Sensory suppression of brain responses to self-generated sounds is observed with and without the perception of agency. *Cortex*, 80, 5-20. <https://doi.org/10.1016/j.cortex.2016.03.018>
- von Holst, E., & Mittelstaedt, H. (1950). Das Reafferenzprinzip. *Naturwissenschaften*, 37(20), 464-476. <https://doi.org/10.1007/BF00622503>

- Weiskrantz, L., Elliott, J., & Darlington, C. (1971). Preliminary Observations on Tickling Oneself. *Nature*, 230(5296), 598-599. <https://doi.org/10.1038/230598a0>
- Widmann, A., & Schröger, E. (2022). Intention-based predictive information modulates auditory deviance processing. *Front Neurosci*, 16, 995119. <https://doi.org/10.3389/fnins.2022.995119>
- Wiggs, C. L., & Martin, A. (1998). Properties and mechanisms of perceptual priming. *Current Opinion in Neurobiology*, 8(2), 227-233. [https://doi.org/10.1016/S0959-4388\(98\)80144-X](https://doi.org/10.1016/S0959-4388(98)80144-X)
- Winkler, I., & Schröger, E. (2015). Auditory perceptual objects as generative models: Setting the stage for communication by sound. *Brain and Language*, 148, 1-22. <https://doi.org/10.1016/j.bandl.2015.05.003>
- Wolpert, D. M. (1997). Computational approaches to motor control. *Trends in Cognitive Sciences*, 1(6), 209-216. [https://doi.org/10.1016/S1364-6613\(97\)01070-X](https://doi.org/10.1016/S1364-6613(97)01070-X)
- Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, 269(5232), 1880-1882. <https://doi.org/10.1126/science.7569931>
- Yon, D., Gilbert, S. J., de Lange, F. P., & Press, C. (2018). Action sharpens sensory representations of expected outcomes. *Nature Communications*, 9(1), 4288. <https://doi.org/10.1038/s41467-018-06752-7>
- Yon, D., Zainzinger, V., de Lange, F. P., Eimer, M., & Press, C. (2021). Action biases perceptual decisions toward expected outcomes. *J Exp Psychol Gen*, 150(6), 1225-1236. <https://doi.org/10.1037/xge0000826>
- Zouridakis, G., Simos, P. G., & Papanicolaou, A. C. (1998). Multiple Bilaterally Asymmetric Cortical Sources Account for the Auditory N1m Component. *Brain Topography*, 10(3), 183-189. <https://doi.org/10.1023/a:1022246825461>

12. Appendix

Table A1

Descriptive Statistics by Analysis Condition

Sequence	Task	N1		P2		N2b	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
One-tone	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
Two-tone	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

		95% <i>CI</i>				<i>df</i>	<i>t</i>	<i>p</i>	<i>d</i>	<i>BF</i> ₁₀
		Est.	<i>SE</i>	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		
			<i>M</i>	<i>SD</i>	<i>Min.</i>	<i>M</i>	<i>SD</i>	<i>Min.</i>
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
One-tone	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
Two-tone	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