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Effects of omission probability on omitted stimulus potentials

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ABSTRACT

Predictions of upcoming sensory events allow the brain to minimize surprises and optimize behavior. When an expected event fails to happen, omitted stimulus potentials (OSPs) occur, consisting of early negative components (oN1 and oN2) and a later positive component (oP3). These OSPs are thought to reflect hierarchical stages of prediction-error signaling, but the functional significance of each component remains unclear. To better characterize these components, this study examined how omission probabilities affect the amplitudes of these components. Participants repeatedly pressed a button at approximately 1-s intervals to trigger a 1000 Hz pure tone. The tone was occasionally omitted, with probabilities of 10%, 20%, 30%, 40%, and 50%. The oN1, oN2, and oP3 components were clearly elicited by low-probability omissions, and their amplitudes decreased systematically as omission probability increased. oN1 and oN2 were largest up to the 20% omission and disappeared at 50%, whereas oP3 remained present across all probability conditions. These results suggest that rarer omissions elicit stronger prediction error responses: oN1 and oN2 appear to index prediction error signaling. In contrast, oP3 is likely to be more closely associated with updating the stimulus context, such as action–effect associations. The present findings provide a useful reference for future OSP research by clarifying how omission probability influences the emergence and magnitude of omission responses.

1. Introduction

The human brain constantly predicts upcoming sensory events, allowing perception and action to proceed efficiently in dynamically changing environments. When sensory input deviates from these predictions, prediction errors arise at multiple hierarchical levels and are propagated upward to shape future predictions (Clark, 2013; Friston, 2005; Rao and Ballard, 1999). Within this framework, less probable events generate larger prediction errors because they constitute more salient deviations from the current model.

Studies using event-related potentials (ERPs) have demonstrated that neural responses scale with event probability, in a manner consistent with prediction error accounts. Mismatch negativity (MMN) is a frontocentral negative potential that peaks at approximately 150–250 ms after the onset of deviant stimuli. It is thought to reflect the detection of violations in auditory regularities (Näätänen et al., 2007) and the resulting prediction error processing (Garrido et al., 2009). Consistent with this view, MMN amplitude has been shown to increase as the probability of a deviant stimulus decreases (Fisher et al., 2011; Sabri and Campbell, 2001).

P3 is also elicited by deviant events and has been linked to prediction error processing at a higher hierarchical level (Chennu et al., 2013; Ghosh et al., 2024). It is characterized as a centroparietal positive deflection, typically peaking around 300–400 ms, and has also been widely interpreted as indexing the evaluation of stimulus value (Johnson, 1986) and updating the representation or schema of the stimulus context, as proposed in the context updating theory (Donchin and Coles, 1988; Polich, 2007). Duncan-Johnson and Donchin (1977) examined P3 amplitudes elicited by standard (1000 Hz) and target (1500 Hz) tones presented at probabilities ranging from 10% to 90% in 10% increments and found that lower probability stimuli elicited larger P3 amplitudes for both types of stimuli.

Omitted stimulus potentials (OSPs) are ERPs that occur when an expected stimulus is unexpectedly omitted (for reviews, see Braga and Schönwiesner, 2022; Heilbron and Chait, 2018; Lao-Rodríguez et al., 2026; Schröger et al., 2015). The OSP waveform typically consists of three components: omission N1 (oN1) at approximately 100 ms, subsequent omission N2 (oN2) at approximately 150–200 ms, and later omission P3 (oP3) at approximately 300–400 ms, observed in response to the omission of self-generated sensory stimuli (Dercksen et al., 2020, 2024; Ishida and Nittono, 2024, 2025; SanMiguel et al., 2013a; Stekelenburg and Vroomen, 2015; Tast et al., 2025). Typically, oN1 and

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oN2 are predominant over the frontocentral or right temporal region, and oP3 shows a centroparietal maximum. The oP3 has also been referred to as an emitted P3 (P3e). Although its relationship to the conventional P3 has been debated (Ruchkin et al., 1980, 1981, 1987; Stapleton et al., 1987), recent literature generally agrees that this positive component is not specific to stimulus omission (Dercksen et al., 2020; Nittono & Sakata, 2009; Prete et al., 2022; Ragazzoni et al., 2019; SanMiguel et al., 2013a; van Laarhoven et al., 2017).

In recent years, OSPs have been increasingly interpreted as reflecting prediction error processing triggered by the unexpected absence of a predicted event. Within the framework of predictive coding, it is generally considered that oN1 reflects an early sensory-level prediction error, oN2 reflects subsequent error processing, and oP3 reflects attention allocation and later model updating at higher cognitive levels (Dercksen et al., 2020; Ishida and Nittono, 2025; SanMiguel et al., 2013a; Tast et al., 2024; Tast et al., 2025; van Laarhoven et al., 2017). If OSPs reflect prediction error processing, their amplitudes should be larger for rarer omissions because less probable omissions result in eliciting larger prediction errors. However, only a few studies have directly examined how omission probability modulates OSP amplitudes.

1.1. Omission probability and OSPs

Busse and Woldorff (2003) examined the effect of omission probability on ERPs in an auditory oddball paradigm, in which 1400 Hz standard tones and 1480 Hz target tones (11%) were presented with a stimulus onset asynchrony (SOA) of 1 or 2 s, and participants were instructed to respond to target tones. Standard tones were occasionally omitted with probabilities of 11%, 22%, and 33% across all trials, while the total number of trials per probability condition was fixed, resulting in different numbers of omission trials across the conditions. In response to omissions, both an early negativity (possibly oN2) and a late positivity (possibly oP3) deviated significantly from the baseline level for all omission probabilities in the 1-s SOA condition and for the 11% omission probability in the 2-s SOA condition. Although no significant amplitude differences were found among the omission probabilities, the results suggested that OSPs tended to be more pronounced for rarer omissions.

Other studies have compared OSPs elicited by the omissions of self-generated stimuli between low- and high-omission probability conditions. SanMiguel et al. (2013b) instructed participants to press a button once per second, and a 1000 Hz tone was presented immediately after each button press. Sounds were omitted on 12% or 50% of button presses, with the total number of omission trials kept constant. In both omission probability conditions, ERPs were compared against the motor control condition, in which button presses were not followed by any sound, serving as a baseline that controlled for movement-related potentials and contained no prediction-related activity associated with stimulus presentation. In the 12% omission, both oN1 and oN2 significantly differed from the motor control condition, whereas in the 50% omission, neither component differed significantly from the control condition. Moreover, both oN1 and oN2 amplitudes were significantly larger in the 12% omission than in the 50% omission. Using the same motor-auditory omission paradigm, Tast et al. (2024) reported similar findings at omission probabilities of 20% and 50% for oN1. Stekelenburg and Vroomen (2015) examined omission responses in both motor-auditory and visual-auditory prediction paradigms. In the visual-auditory condition, audiovisual clips of hand clapping were presented, and the hand-clap sound was omitted in 12% or 50% of the trials, with omission counts matched across conditions. After subtracting the modality-specific baseline (visual only or motor only), oN1 did not differ between 12% and 50%, whereas oN2 and oP3 were significantly larger in 12% than in 50%. Follow-up tests further showed that oN2 was significantly different from zero in the 12% omission but not in the 50% omission.

Extending these findings to the somatosensory domain, Dercksen et al. (2024) reported that somatosensory oN1, oN2, and oP3 (extracted via temporal principal component analysis) differed significantly from the motor control condition at 12% omission but not at 50% omission, and that all components were larger at 12% omission than at 50% omission. Together, these studies suggest that OSP amplitudes increase when omissions become less probable, indicating that rarer omissions elicit greater prediction errors.

1.2. Current study

The available evidence points to larger OSPs for rarer omissions, but most studies have contrasted only two probability levels (e.g., low vs. high probability). It remains unclear how sensitively OSP amplitudes vary across different levels of omission probability. The study by Busse and Woldorff (2003) implemented the most fine-grained manipulation of omission probability to date, but because the stimuli were presented automatically with relatively long SOAs, the resulting temporal jitter in OSP latency may have affected the amplitude measurements.

To address these issues, the present study varied the omission probability from 10% to 50% in 10% increments and compared the amplitudes of the oN1, oN2, and oP3 components. By presenting stimuli in synchrony with participants' voluntary button presses, we aimed to minimize the latency jitter in detecting omissions. Auditory stimuli were presented immediately after each button press and omitted at five probability levels across the conditions. The participants' voluntary actions were registered using a force-sensitive resistor pad instead of a mouse button with an audible click. This apparatus minimized external stimulation at the time of omission by eliminating both the click sound and tactile feedback associated with button clicks. It also recorded the force exerted during each button press. We expected the OSP amplitudes to increase as the probability of stimulus omission decreased, reflecting larger prediction errors when highly probable sensory inputs were unexpectedly omitted.

2. Methods

2.1. Participants

The sample size was determined using the following rationale. The oN1, oN2, and oP3 amplitudes were planned to be compared separately across five conditions using one-way repeated-measures ANOVAs with a factor of omission probability. A power analysis using G*power (Faul et al., 2007) indicated that 33 participants would be required to detect a moderate effect ($f = 0.25$) in a one-way five-level repeated-measures ANOVA ($\alpha = 0.05$, $1 - \beta = 0.80$, $r = 0.50$, and $\varepsilon = 0.50$). Additionally, detecting a paired difference with an effect size of $dz = 0.5$ at 80% power would require 34 participants.

To secure this sample size, a total of 46 participants were recruited, and 36 participants (13 males and 23 females, 18–37 years old, $M =$ 22.3 years old) were included in the final analysis according to the criteria detailed below. All participants were right-handed according to the FLANDERS handedness questionnaire (Okubo et al., 2014) and self-reported normal vision and hearing. Written informed consent was obtained from all participants before the experiment. Participants received a cash voucher of 3500 Japanese yen as an honorarium. The study protocol was approved by the Behavioral Research Ethics Committee of the University of Osaka, School of Human Sciences, Japan (H025–034), in accordance with the Declaration of Helsinki.

2.2. Stimuli and apparatus

The standard and target stimuli were 1000-Hz and 1050-Hz pure tones, respectively (16-bit quantization, 48-kHz A/D sampling), each presented for 70 ms (10-ms rise/fall) at 60 dB SPL. These stimuli were presented binaurally through canal-type (closed-type) earphones (MDR-EX650AP; SONY, Tokyo, Japan) using an Ez-SOUND sound stimulus

system (Nihon Santeku, Osaka, Japan). To reduce the sound and tactile feedback from button clicks, the voluntary actions of the participants were registered using a force-sensitive resistor pad (MF01A-N-221-A0; Taiwan Alpha Electronic, Taoyuan, Taiwan; diameter 10.2 mm), which was covered with a felt sheet and placed on a rubber sheet on the desk. The pad was connected to an Arduino microcontroller (UNO R4 WiFi, ABX00087; Arduino, Ivrea, Italy).

When the pressing force exceeded the preset threshold (0.3 N), the Arduino, which was running a program written in Arduino IDE 2.3.6, issued a TTL signal to the experimental PC. Upon receiving this TTL signal, Inquisit 6.5.1 (Millisecond Software, Seattle, WA, USA), running on the experimental PC, sent a synchronized TTL signal to the Ez-SOUND for generating tones and to the electroencephalography (EEG) amplifier for recording stimulus triggers. This configuration was adopted to minimize the delay and temporal jitter from the participants' voluntary actions to stimulus presentation relative to a conventional setup in which button presses are registered as mouse button or keyboard inputs via serial communication. The continuous force values from the force-sensitive resistor pad were simultaneously recorded using an auxiliary EEG channel. Throughout the task, a small landscape image (8.0 cm × 4.5 cm) was presented at the center of a ViewPixx monitor (VPixx Technologies, Quebec, Canada; 120 Hz) as a fixation, viewed from a distance of 80 cm, to keep the gaze steady and prevent boredom.

2.3. Procedure

Fig. 1 illustrates the experimental design of this study. Participants were asked to tap the force-sensitive resistor pad with their index finger at a constant interval of approximately 1 s. Hereafter, this action is referred to as a "button press" to align with previous research. For each button press, either a standard tone (1000 Hz) or a target tone (1050 Hz) was presented. The hand used to trigger the stimulus was counterbalanced among the participants. The target tone was presented randomly in 10% of the trials, and the participants were required to respond to the target tones by pressing another button using the thumb of the opposite hand.

In some trials, no tone was presented following a button press (omission trials). The probability of omission trials varied across the probability conditions. Five omission probability conditions (10%, 20%, 30%, 40%, and 50%) were tested, with the number of omission trials fixed at 140. Each condition was divided into 1–4 blocks (see Fig. 1) to keep the duration of each block approximately constant (5–6 min). In addition, at the beginning and end of the experiment, the participants performed a motor control condition. They were instructed to press a button at the same pace as in the omission probability conditions, without any stimulus following, 80 times each (160 times in total). The data were used to correct the movement-related potentials in the ERP waveforms. The entire experiment took approximately two and a half hours, including electrode preparation and short breaks between blocks.

The participants were instructed to fixate on the small landscape image on the monitor throughout the task. They were informed that occasionally no tone would be presented after a button press, and that the frequency of such omissions varied across blocks. However, the specific omission probability for each block was not disclosed.

The first four trials of each block and two trials following the target trial were standard trials. In the 10% and 20% omission conditions, at least two trials following an omission trial were standard trials. In the 30% omission condition, at least one trial following an omission trial was a standard trial. In the 40% and 50% omission conditions, the number of consecutive omission trials was limited to three trials. The order of the probability conditions was counterbalanced across participants (10 possible orders). For conditions consisting of multiple blocks, the blocks were performed in sequence. Twenty practice trials were provided at the beginning of the experiment to familiarize participants with maintaining the appropriate button-press interval.

2.4. Data recording

EEG data were recorded using a QuickAmp (Brain Products, Germany) with Ag/AgCl electrodes. Thirty-four scalp electrodes were used according to the 10–20 system (Fp1/2, F3/4, F7/8, Fz, FC1/2, FC5/6, FT9/10, C3/4, T7/8, Cz, CP1/2, CP5/6, TP9/10, P3/4, P7/8, Pz, O1/2, Iz, and PO9/10). The EEG was recorded with an online average reference, and the ground electrode was placed at AFz. Additional electrodes were placed on the nose tip for offline re-referencing, as well as on the left and right outer canthi of the eyes and above and below the right eye. The sampling rate was set to 1000 Hz. The online filter was set to DC–200 Hz. The electrode impedance was maintained below 10 kΩ.

2.5. Exclusion criteria

A button press that occurred within 600–1400 ms after the previous button press was counted as a correct response, in accordance with the criteria used by Ishida and Nittono (2025). This time window was defined to allow a sufficiently long post-button-press interval for ERP analysis (600 ms) including oP3. The upper limit was determined symmetrically around the instructed 1-s button-press interval (1000 ± 400 ms). Button presses outside this range were counted as button-press errors; however, the corresponding tones were still presented to keep the omission probability constant. Button-press error trials were excluded from the analyses. Late responses to the target tone (more than 1000 ms after the onset of the target tone) or no responses during the target trials were recorded as target detection errors. Trials immediately following target trials, and trials containing a false alarm response in the period of 1400 ms before and 500 ms after a standard tone or omission were excluded from the analyses.

A total of 10 participants were excluded from the analysis based on the following criteria: 42 or more rejected omission trials in any probability condition (30% of the 140 omission trials) due to artifacts ($n = 2$); 10% or more button-press errors in any probability condition ($n = 7$); FLANDERS Handedness Questionnaire score of −5 or lower, indicating left-handedness ($n = 1$); and 70% or fewer hits and/or 15% or more false

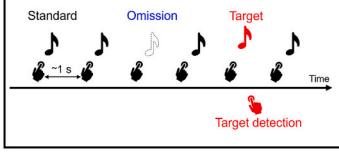
Task sequence	Omission probability	Omission	Standard	Target	Total blocks
	10%	140 (0.10)	1,120 (0.80)	140 (0.10)	4
	20%	140 (0.20)	490 (0.70)	70 (0.10)	2
	30%	140 (0.30)	279 (0.60)	47 (0.10)	2
	40%	140 (0.40)	175 (0.50)	35 (0.10)	1
	50%	140 (0.50)	112 (0.40)	28 (0.10)	1
	Control (100%)	160 (1.00)	0 (0.00)	0 (0.00)	2

Fig. 1. Experimental design. *Note.* The task sequence with three types of trials (omission, standard, and target), omission probability (10%–50%), and control conditions, and the number and proportion of each trial type for each probability condition. The participants pressed a button at self-paced intervals of approximately 1 s. A 1000-Hz pure tone (standard tone) was usually presented immediately after each button press, whereas a 1050-Hz pure tone (target tone) was presented in 10% of the trials. In some trials, the tone was omitted with different probabilities. The participants were instructed to respond to the target tones with their opposite hands. In the motor control condition, button presses were not followed by any stimuli (100% omission).

alarms in the target trials ($n = 0$). Consequently, data from 36 participants were included in the analysis. For these, the mean percentages of button-press error trials were 1.29% (range = 0.0%–6.7%, $SD = 1.15$) in the omission probability conditions and 0.97% (range = 0.0%–5.6%, $SD = 1.34$) in the motor control condition. For target detection, the mean hit rate was 96.8% (range = 80%–100%, $SD = 4.6$), and the false alarm rate was 0.1% (range = 0.0%–0.4%, $SD = 0.1$).

2.6. Processing of EEG data

The EEG data were analyzed using EEGLAB (Delorme and Makeig, 2004; version 2023.1) on MATLAB R2023b (MathWorks, Natick, MA, USA). Following the procedure of Ishida and Nittono (2025), a digital bandpass filter of 0.1–30 Hz was applied. Eye blinks and eye-movement-induced artifacts were corrected based on independent component analysis. The epochs 200 ms before and 600 ms after stimulus omission were averaged for each condition. Epochs with voltage differences greater than 80 μV were removed. The mean rejection rates were 5.0% (range = 0.0%–20.0%, $SD = 5.8$) for the 10% omission trials, 4.7% (range = 0.0%–22.9%, $SD = 5.8$) for the 20% omission trials, 5.1% (range = 0.0%–26.4%, $SD = 6.2$) for the 30% omission trials, 3.5% (range = 0.0%–17.9%, $SD = 4.6$) for the 40% omission trials, 4.0% (range = 0.0%–27.1%, $SD = 6.4$) for the 50% omission trials, and 3.4% (range = 0.0%–13.8%, $SD = 3.3$) for the motor control condition. Baseline correction was performed by subtracting the mean amplitude of the initial 200-ms period from the amplitude of the entire averaged waveform at each point. To correct for movement-related potentials, the ERP waveforms of the motor control condition were subtracted from those of the probability conditions. Based on previous studies (Dercksen et al., 2020; Ishida and Nittono, 2025; SanMiguel et al., 2013a) and visual inspection of the scalp topographies, two regions of interest (ROIs) were defined for analysis: central (FC1, FC2, Cz, CP1, and CP2) and right temporal (FC6, T8, and CP6) regions.

For the statistical evaluation of OSPs, the grand mean difference (motor-corrected) waveforms of the omission trials in all probability conditions were averaged. In this waveform, peak latencies were detected in the right temporal ROI within 50–150 ms for oN1, 150–250 ms for oN2, and in the central ROI within 250–550 ms for oP3. Around each peak, the time windows were defined as ±10 ms for oN1, ±30 ms for oN2 from the negative peaks, and ± 50 ms for oP3 from the positive peak, based on Ishida and Nittono (2025) and visual inspection of the data. Consequently, the time windows 110–130 ms, 174–234 ms, and 270–370 ms were defined as the oN1, oN2, and oP3 intervals, respectively, and the mean ERP amplitudes were calculated for each probability condition from these intervals.

Although not initially planned for examination, a frontal negativity resembling feedback-related negativity (FRN; Walsh and Anderson, 2012) was observed, consistent with the results of Ishida and Nittono (2024). The FRN was analyzed within the frontal ROI (F3, Fz, and F4), where it showed a maximal amplitude. The negative peak latency was identified within 150–250 ms, and a ± 20 ms interval centered on this peak was defined as 150–190 ms for amplitude measurement.

2.7. Behavioral measures

The following behavioral measures were computed for each participant separately for each probability condition and, where applicable, for the motor control condition. The interval between a given button press at trial n and the immediately following button press at trial $n + 1$ was defined as the button-press interval for trial n. First, the mean button-press intervals were compared across the five probability conditions and motor control condition to confirm the stability of button-press pacing across conditions. To further examine whether action effects influenced button-press pacing, we analyzed whether the button-press interval and the button-press force differed depending on the trial type (omission, standard, or target). The button-press force (N) in each trial was quantified as the mean force value within a 25–200 ms window relative to the button press (0 ms). The waveforms of the button-press force for all conditions, including the motor control condition, are shown in Supplementary Material Fig. S1. Button-press interval error rates, reaction times (RTs) to target stimuli, target detection error rates, and false alarm rates were also calculated.

2.8. Statistical analysis

All statistical analyses were conducted using JASP 0.95.4 (JASP Team, 2025) and R 4.5.1 (R Core Team, 2025). Both classical (frequentist) and Bayesian analyses were performed to statistically evaluate the ERP amplitudes and behavioral measures. The type I error rate (α) was set at 0.05. For multiple comparisons, the Bonferroni correction was applied to control for the type I error rate. For Bayesian *t*-tests, Bayes factors were calculated to compare the null hypothesis of effect size $\delta = 0$ against a two-sided alternative hypothesis ($\delta \neq 0$; BF_{10}) or a one-sided directional alternative hypothesis ($\delta < 0$ or $\delta > 0$; BF_{-0} or BF_{+0}, depending on the expected direction) under the default Cauchy prior ($r = 0.707$), following Wagenmakers et al. (2018b). For Bayesian repeated-measures ANOVAs, Bayes factors were used to compare a set of candidate models that differed in whether they included each effect of interest, such as main effects and interactions (Rouder et al., 2012). These models were evaluated under the default prior settings implemented in JASP, with Cauchy prior widths of $r = 0.5$ for fixed effects, $r = 1$ for random effects, and $r = 0.354$ for covariates. Evidence for each effect was summarized using the inclusion Bayes factor (BF_{incl}), which quantifies the relative support for models that include the effect versus matched models that exclude the effect (Wagenmakers et al., 2018a). In accordance with Schönbrodt and Wagenmakers (2018), Bayes factors ranging from 1 to 3 were regarded as anecdotal evidence in favor of the effect of interest, and Bayes factors exceeding 3 were considered moderate evidence.

Statistical analyses of OSPs were conducted in two steps. First, to confirm the presence of OSPs, one-tailed one-sample *t*-tests and their Bayesian counterparts were performed against zero on the mean amplitudes of oN1, oN2, and oP3 in the difference waveforms for each probability condition. Second, to evaluate how omission probability modulated OSP amplitudes, one-way repeated-measures ANOVAs and their Bayesian counterparts were conducted separately on the oN1, oN2, and oP3 amplitudes. In addition, a two-way repeated-measures ANOVA (Component × Omission probability) and its Bayesian counterpart were performed to examine whether the effect of omission probability differed across OSP components. Sphericity corrections were applied by adjusting the degrees of freedom using Greenhouse-Geisser ε.

Error rates, including button-press error rates and hit and false alarm rates for target detection, were compared across probability conditions (and the motor control condition for button-press error rates only) using one-way repeated-measures ANOVAs and their Bayesian counterparts.

The mean button-press interval and force, and target RTs were analyzed using linear mixed-effects models (LMMs) fitted with the *lme4* package (Bates et al., 2015) in R to examine the effects of conditions. In all LMM analyses, participant was included as a random factor. Following Barr et al. (2013) and Luke (2017), the random effects structure was determined by comparing candidate models with different random slopes based on convergence, singularity, and Akaike's information criterion (AIC). Fixed effects and their interactions, when applicable, were tested using type III ANOVAs with Satterthwaite's approximation for degrees of freedom (*lmerTest* package; Kuznetsova et al., 2017). Post hoc comparisons were conducted using the *emmeans* package (Lenth, 2025).

First, the effects of condition (five probability conditions and motor control condition) on the mean button-press interval and mean button-press force were analyzed. Condition was included as a fixed effect, and the final models included random intercepts for participants and random slopes for condition for both the mean interval and force.

Second, the effects of trial type (omission, standard, or target) and omission probability on the button-press interval and force were analyzed. Trial type and probability condition were included as fixed effects. The final models included a random intercept for participant. Random slopes for trial type and probability condition were included for the button-press interval, whereas only a random slope for probability condition was included for the button-press force. Finally, the effect of omission probability on target RTs was analyzed. Probability condition was included as a fixed effect, and the final model included a random intercept for participant and a random slope for omission probability condition. In addition, to further characterize systematic changes across the five levels of omission probability (10%–50%), polynomial trend analyses up to the fourth order (linear, quadratic, cubic, and quartic) were conducted for the ERP amplitudes and behavioral measures.

3. Results

3.1. ERPs

Fig. 2 illustrates the motor-corrected grand mean ERP waveforms of omission trials for the five probability conditions and motor control condition, as well as the motor-corrected scalp topographies of the mean amplitudes in the oN1, FRN, oN2, and oP3 intervals. The original (uncorrected) ERP waveforms of omission trials are shown in Supplementary Material Fig. S2. The ERP waveforms for the standard and target trials are shown in Supplementary Material Figs. S3 and S4. Movement-related positive potentials were predominant over the frontal-to-central regions, which were superimposed by deflections corresponding to oN1, oN2, and oP3. oN1 and oN2 were predominant in the right temporal region. oP3 showed a central distribution with a slightly left-lateralized focus. In the 10% and 20% omission conditions, a frontal negative deflection resembling the FRN emerged slightly earlier than the temporal-dominant oN2.

Table 1 shows the ERP amplitudes and the results of the one-tailed one-sample *t*-tests against a zero baseline. Table 2 summarizes the main effects of omission probability and key pairwise differences for each ERP component. The mean amplitudes of the oN1 and oN2 components deviated significantly from zero in the 10%, 20%, 30%, and 40% conditions ($ps \leq 0.011$, $BF_{-0} \geq 4.31$), but not in the 50% condition ($ps \geq 0.415$, $BF_{-0} \leq 0.21$). A one-way repeated-measures ANOVA on oN1 amplitudes revealed a significant main effect of omission probability, $F(4, 140) = 6.87$, $p < .001$, $\eta_p^2 = 0.16$, Greenhouse-Geisser $\varepsilon = 0.774$, $BF_{incl} > 100$. Post hoc *t*-tests indicated that amplitudes in the 10%, 20%, and 40% conditions were significantly larger than that in the

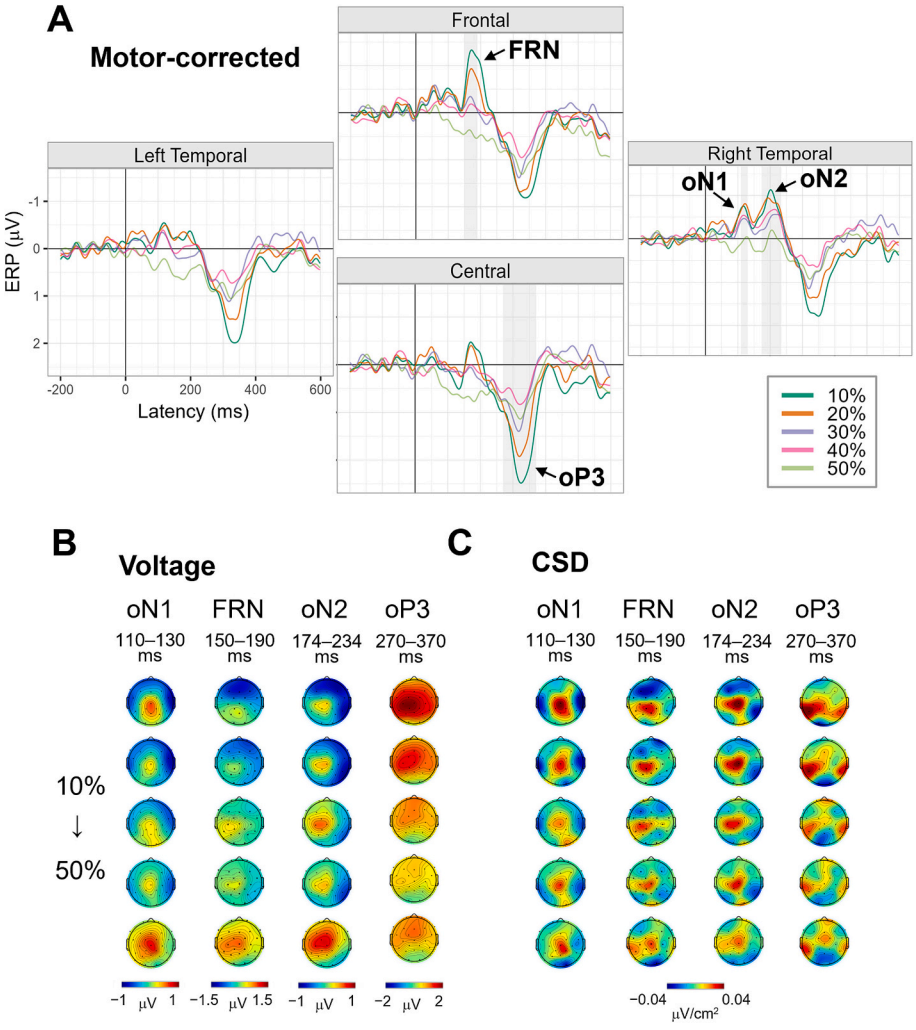


Fig. 2. Grand Mean Motor-Corrected ERP Waveforms of Omission Trials
Note. (A) Motor-corrected ERP waveforms of omission trials for the 10%–50% probability conditions, averaged across frontal electrodes (F3, Fz, and F4), central electrodes (FC1, FC2, Cz, CP1, and CP2), left temporal electrodes (FC5, T7, and CP5), and right temporal electrodes (FC6, T8, and CP6). The gray area indicates the oN1 (110–130 ms), FRN (150–190 ms), oN2 (174–234 ms), and oP3 (270–370 ms) intervals. (B) Scalp topographies in the oN1, FRN, oN2, and oP3 intervals. (C) Corresponding current source density (CSD) maps.

Table 1
Means, standard deviations, and comparisons of ERP amplitudes against zero.

N = 36	Probability	M (SD)	t $df = 35$	p	dz	$BF_{-0/+0}$
oN1	10	−0.74 (1.14)	−3.87	< 0.001	−0.65	> 100
	20	−0.87 (1.18)	−4.42	< 0.001	−0.74	> 100
	30	−0.59 (1.14)	−3.11	0.002	−0.52	19.76
	40	−0.58 (1.05)	−3.34	< 0.001	−0.56	34.27
	50	−0.05 (1.38)	−0.22	0.415	−0.04	0.21
oN2	10	−0.93 (1.63)	−3.44	< 0.001	−0.57	43.23
	20	−0.90 (1.81)	−3.00	0.002	−0.50	15.42
	30	−0.51 (1.27)	−2.40	0.011	−0.40	4.31
	40	−0.62 (1.08)	−3.44	< 0.001	−0.57	42.84
	50	−0.03 (1.20)	−0.15	0.442	−0.03	0.20
oP3	10	1.98 (2.29)	5.17	< 0.001	0.86	> 100
	20	1.47 (1.76)	5.02	< 0.001	0.84	> 100
	30	0.93 (1.98)	2.82	0.004	0.47	10.28
	40	0.57 (2.01)	1.70	0.049	0.28	1.24
	50	0.89 (2.10)	2.54	0.008	0.42	5.67
FRN	10	−1.19 (1.71)	−4.20	< 0.001	−0.70	> 100
	20	−0.82 (1.94)	−2.55	0.008	−0.43	5.86
	30	−0.25 (1.05)	−1.41	0.084	−0.23	0.80
	40	−0.13 (1.01)	−0.76	0.227	−0.13	0.36
	50	0.43 (1.40)	1.85	0.963	0.31	0.07

Note. Results of one-tailed one-sample *t*-tests and corresponding Bayesian *t*-tests are shown.

Table 2
Summary of omission probability effects and key pairwise contrasts for ERP amplitudes.

N = 36	Main effect of omission probability	Key pairwise differences	Polynomial contrasts
oN1	$F(4, 140) = 6.87$, $p < .001$, $\eta_p^2 = 0.16$, $BF_{incl} > 100$	10%–40% > 50%	Linear and quadratic
oN2	$F(4, 140) = 5.63$, $p = .003$, $\eta_p^2 = 0.14$, $BF_{incl} = 74.11$	10%–40% > 50%	Linear and quartic
oP3	$F(4, 140) = 8.29$, $p < .001$, $\eta_p^2 = 0.19$, $BF_{incl} > 100$	10% > 30%–50% 20% > 40%	Linear and quadratic
FRN	$F(4, 140) = 11.43$, $p < .001$, $\eta_p^2 = 0.25$, $BF_{incl} > 100$	10% > 30%–50% 20% > 50%	Linear

Note. This table summarizes the results of one-way repeated-measures ANOVAs and key pairwise contrasts (10%–50% omission probability) for the oN1, oN2, oP3, and FRN amplitudes.

50% condition ($ps \leq 0.027$, $BF_{10} \geq 13.01$). The difference between the 30% and 50% conditions did not reach significance in the frequentist test (p =08104); however, Bayesian hypothesis testing using Bayes factors provided moderate evidence for the difference ($BF_{10} = 4.08$). Polynomial trend analysis revealed a significant linear trend, $t(35) = 3.38$, $p = .002$, $dz = 0.44$, and a quadratic trend, $t(35) = 2.43$, $p = .020$, $dz = 0.24$.

Similarly, a one-way repeated-measures ANOVA on oN2 amplitudes showed a significant main effect of omission probability, $F(4, 140) = 5.63$, $p = .003$, $\eta_p^2 = 0.14$, Greenhouse-Geisser $\varepsilon = 0.615$, $BF_{incl} = 74.38$. The oN2 amplitudes in the 10%, 20%, and 40% conditions were significantly larger than that in the 50% condition ($ps \leq 0.021$, $BF_{10} \geq 16.64$). For the difference between the 30% and 50% conditions, the frequentist test did not reach statistical significance ($p = .145$); however, Bayesian hypothesis testing using Bayes factors provided moderate evidence for the difference ($BF_{10} = 3.09$). The oN2 amplitudes exhibited a significant linear trend, $t(35) = 3.10$, $p = .004$, $dz = 0.47$, and a quartic trend, $t(35) = 2.27$, $p = .030$, $dz = 0.17$. Numerically, the oN1 and oN2 amplitudes were largest (i.e., most negative) in the 10% and 20% conditions, followed by the 30% and 40% conditions, and smallest in the 50% condition. The overall linear trend was accompanied by a stepwise pattern, particularly evident for oN2, as indicated by the significant quartic trend observed for this component.

For oP3, the mean amplitude deviated significantly from zero in all conditions ($ps \leq 0.049$), although the evidence was anecdotal in the 40% condition ($BF_{+0} = 1.24$). A one-way repeated-measures ANOVA revealed a significant main effect of omission probability, $F(4, 140) = 8.29$, $p < .001$, $\eta_p^2 = 0.19$, Greenhouse-Geisser $\varepsilon = 0.835$, $BF_{incl} > 100$. The oP3 amplitude was significantly larger in the 10% condition than in the 30%, 40%, and 50% conditions, and larger in the 20% condition than in the 40% condition ($ps \leq 0.028$, $BF_{10} \geq 12.78$). Trend analysis revealed a significant linear trend, $t(35) = -4.61$, $p < .001$, $dz = -0.48$, and a quadratic trend, $t(35) = 2.46$, $p = .019$, $dz = 0.24$. Numerically, the oP3 amplitudes were largest in the 10% condition, followed by the 20%, 30%, 50%, and 40% conditions.

For the FRN, the mean amplitude deviated significantly from zero in the 10% and 20% conditions ($ps \leq 0.008$, $BF_{-0} \geq 5.86$). A one-way repeated-measures ANOVA revealed a significant main effect of omission probability, $F(4, 140) = 11.43$, $p < .001$, $\eta_p^2 = 0.25$, Greenhouse-Geisser $\varepsilon = 0.665$, $BF_{incl} > 100$. The FRN amplitude was significantly more negative in the 10% condition than in the 30%–50% conditions, and in the 20% condition than in the 50% condition ($ps \leq 0.008$, $BF_{10} \geq 36.47$). Trend analysis revealed a significant linear trend, $t(35) = 4.78$, $p < .001$, $dz = 0.85$.

Fig. 3 illustrates how the OSP amplitudes changed with omission probability. The mean amplitudes of the negative-going components (oN1 and oN2) were sign-inverted so that all values represented deviations from the baseline in a positive direction. The oN1, oN2, and oP3 amplitudes were largest in low-probability omission and gradually diminished as omission probability increased, but the modulation pattern appeared to differ between the early components (oN1 and oN2), which showed highly similar patterns, and the late component (oP3), which showed a distinct pattern. A two-way repeated-measures ANOVA with the factors component (oN1, oN2, oP3) and omission probability (10%–50%) revealed a significant interaction between component and omission probability, $F(8, 280) = 2.59$, $p = .035$, $\eta_p^2 = 0.07$, Greenhouse-Geisser $\varepsilon = 0.544$, $BF_{incl} = 9.08$. However, simple

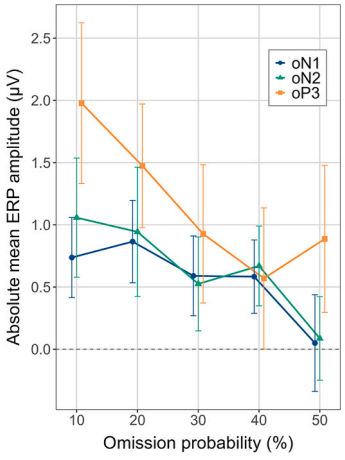


Fig. 3. Absolute mean ERP amplitudes of oN1, oN2, and oP3 as a function of omission probability. *Note.* Error bars indicate 90% confidence intervals corresponding to one-tailed one-sample *t*-tests (α = 0.05). The mean amplitudes of the negative-going components (oN1 and oN2) were sign-inverted.

effects contrasts showed that the absolute mean amplitude differed significantly only between oN1 and oP3 in the 10% condition ($p = .016$).

3.2. Behavioral measures

Table 3 shows the means and standard deviations of behavioral measures. First, the LMM revealed a significant main effect of the probability condition on the mean button-press intervals, $F(5, 35.02) = 20.52$, $p < .001$, $\eta_p^2 = 0.75$. Post hoc *t*-tests revealed that the button-press interval was significantly longer in the motor control condition (948 ms) than in all probability conditions (854–872 ms) ($ps \leq 0.001$), whereas no significant differences were observed among the probability conditions ($ps = 1.00$). A repeated-measures ANOVA on the mean button-press error rates also revealed a significant main effect of omission probability, $F(5, 175) = 2.83$, $p = .025$, $\eta_p^2 = 0.08$, Greenhouse-Geisser $\varepsilon = 0.841$, $BF_{incl} = 3.35$. A significant linear contrast across the omission probability conditions ($p = .004$) indicated that the error rate decreased linearly with the omission probability.

Post hoc *t*-tests further showed that the error rate was significantly higher in the 10% condition (1.7%) than in the 50% condition (0.8%) ($p = .015$). For the mean button-press force, the LMM did not reveal a significant main effect of the conditions, $F(5, 35.04) = 2.01$, $p = .101$, $\eta_p^2 = 0.22$. However, exploratory polynomial trend analysis across the omission probability conditions (10%–50%) revealed a significant linear trend ($p = .025$), indicating that the button-press force tended to increase as the omission probability increased.

Fig. 4 shows how button-press intervals and force varied as a function of the three trial types (omission, standard, and target) and five probability conditions. For the button-press interval, the LMM revealed a significant main effect of trial type, $F(2, 35) = 18.90$, $p < .001$, $\eta_p^2 = 0.52$. The Trial type × Probability condition interaction was also significant, $F(8, 111007) = 14.95$, $p < .001$, $\eta_p^2 < 0.01$, although the effect size was negligible. The main effect of probability was not significant ($p = .495$). Post hoc comparisons indicated that the omission–standard and target–standard differences were significant across all omission probabilities, whereas the omission–target difference reached significance only in the 30% and 40% conditions ($ps \leq 0.034$). Polynomial trend analyses within each trial type showed no evidence of linear-to-quartic trends across omission probabilities ($ps \geq 0.140$).

For the button-press force, the LMM revealed a significant main effect of trial type, $F(2, 110564) = 7.72$, $p < .001$, $\eta_p^2 < 0.01$ (the effect size was negligible). Post hoc comparisons indicated that the omission–target and standard–target differences were significant ($ps \leq 0.001$). The main effect of probability did not reach significance, $F(4, 35) = 2.51$, $p = .059$, $\eta_p^2 = 0.22$. However, significant positive linear trends were observed in all trial types ($ps \leq 0.018$), indicating that the button-press force tended to increase as the omission probability increased. The Trial type × Probability condition interaction was not significant, $F(8, 110565) = 1.55$, $p = .136$, $\eta_p^2 < 0.01$.

Table 3
Means and standard deviations of behavioral measures for button press and target detection.

$N = 36$	Omission probabilities					
	10%	20%	30%	40%	50%	control
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Button-press						
Interval (ms)	870 (120)	870 (112)	865 (142)	872 (128)	854 (119)	948 (88)
Error rate (%)	1.7 (1.9)	1.4 (1.7)	1.5 (1.7)	1.0 (1.4)	0.8 (1.1)	1.0 (1.3)
Force (N)	0.9 (0.4)	1.0 (0.4)	0.9 (0.5)	1.0 (0.5)	1.0 (0.5)	0.9 (0.4)
Target detection						
RT (ms)	436 (59)	436 (57)	455 (64)	445 (65)	430 (75)	
Hit rate (%)	97.8 (2.8)	97.3 (4.7)	96.6 (6.6)	93.8 (12.1)	94.9 (10.6)	
False alarm (%)	0.09 (0.1)	0.1 (0.2)	0.1 (0.2)	0.1 (0.2)	0.2 (0.3)	

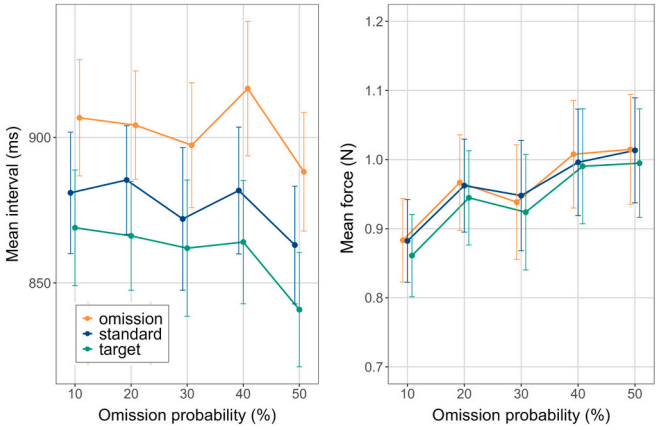


Fig. 4. Button-press interval and force. *Note.* Button-press interval (left) and button-press force (right) for each trial type (omission, standard, and target) as a function of omission probability. Error bars indicate standard error of the mean.

For the target RTs, the LMM revealed a significant main effect of omission probability, $F(4, 33.98) = 3.35$, $p = .021$, $\eta_p^2 = 0.28$. Post hoc *t*-tests showed that target RTs were significantly longer in the 30% condition (455 ms) than in the 10% (436 ms) and 50% conditions (430 ms) ($ps \leq 0.042$). Consistent with this pattern, polynomial trend analysis revealed a significant quadratic trend ($p = .013$), indicating an inverted U-shaped relationship, such that target RTs were slowest at the intermediate omission probability (30%) and faster at both the lowest (10%) and highest (50%) probabilities.

For the target hit rate, a repeated-measures ANOVA showed a significant main effect of omission probability, $F(4, 140) = 3.24$, $p = .045$, $\eta_p^2 = 0.09$, Greenhouse-Geisser $\varepsilon = 0.501$, $BF_{incl} = 2.16$. A significant negative linear trend was observed ($p = .034$), indicating that the hit rate decreased as the omission probability increased; however, post hoc *t*-tests showed that no pairwise differences were significant ($ps \geq 0.234$). For the false alarm rate, no significant main effect of omission probability was found, $F(4, 140) = 1.36$, $p = .257$, $\eta_p^2 = 0.04$, Greenhouse-Geisser $\varepsilon = 0.785$, $BF_{incl} = 0.15$. The false alarm rates were uniformly low across all probabilities ($\leq 0.2\%$), and no trends were observed ($ps \geq 0.051$).

4. Discussion

The present study investigated how the probability of stimulus omission modulates OSP amplitudes. Across components, the OSP amplitudes decreased as the omission probability increased, showing a significant linear trend: oN1, oN2, and oP3 were largest in the low-probability omission (10%–20%) and smallest in the high-probability omission (40%–50%), supporting our hypothesis. These findings indicate that rarer omissions elicit stronger prediction error responses in both early (oN1 and oN2) and late (oP3) processing stages, in line with the predictive coding accounts of OSPs.

4.1. Morphology of OSPs

oN1 and oN2 were predominant over the right temporal region, and oP3 showed a central maximum, consistent with the results of Ishida and Nittono (2024). oP3 showed a slightly left-lateralized distribution. This lateralization may reflect task-dependent demands, such as responding to targets with the opposite hand and experiencing multiple action–effect contingencies, neither of which was required in Ishida and

Nittono.

Unlike Ishida and Nittono (2025), a clear oP3 was observed in this study. This discrepancy was likely because the target probability in the earlier study was extremely low (1%–2%), whereas participants in the present study were required to respond to 10% of stimuli. oP3 emergence in this study may have been partly facilitated by a generally higher level of attentional engagement (e.g., Luck and Kappenman, 2012). Another possible explanation is the difference in the informational value of stimulus omission. In Ishida and Nittono (2025), omission trials did not convey additional information because the probability of omission was fixed ($p = .12$). In contrast, in the present study, the omission probability changed across blocks. Thus, omissions were useful for updating the participant's mental models of the current stimulus context. This greater informational significance could have facilitated the emergence of oP3 (Johnson, 1986).

The FRN appeared under low omission probability conditions, as in Ishida and Nittono (2024). Because the present task employed a force-sensitive resistor pad instead of a computer mouse, participants did not receive explicit click feedback confirming successful action execution. When omissions were infrequent, the stimuli followed participants' presses with relatively high reliability, thereby strongly biasing participants to expect a stimulus after each press. Under these conditions, an omitted outcome may have been interpreted as a sign that the preceding action was ineffective (button press too weak), thereby engaging an action-monitoring process reflected in the FRN.

Importantly, this interpretation does not imply that rare omissions necessarily induce an increase in button-press force. Because most presses still produced stimuli, there was little need to adjust the force of subsequent presses. Under high omission probabilities, participants may have slightly increased the button-press force to ensure an effective response. As reviewed by San Martín (2012), FRN-related processes may be dissociated from behavioral adjustment mechanisms, as the FRN can occur without subsequent behavioral adaptation and vice versa. Accordingly, the occurrence of FRN under low omission probability conditions and the gradual increase in force under high-omission probability conditions may reflect dissociable processes: transient performance monitoring versus sustained adaptive control.

The oN1 peak in the present study was at 120 ms, which is later than the typical 50–100 ms latency reported in previous OSP studies. This corresponds to the late oN1 described by Korka et al. (2020), who distinguished an early oN1 peaking at 94 ms and a late oN1 at 152 ms based on temporal principal component analysis (PCA). They proposed that the early oN1 reflected the sensory activation of the predicted input, whereas the late oN1 indexed higher-level prediction error processing. Dercksen et al. (2022) and Tast et al. (2025) likewise reported early and late oN1 components, both again based on temporal PCA. In the present data, a small peak around 100 ms was also visible in the frontal area, which may correspond to the conventional or early oN1 component. Experiencing multiple omission probabilities may have made it difficult to form a single, stable predictive representation. As a result, sensory pre-activation (reflected by the early oN1) may have been weakened, whereas subsequent prediction error processing (reflected by the late oN1) became more predominant. Determining the circumstances that elicit early and late oN1 and the distinct predictive processes they reflect remains a key task for future studies.

4.2. Omission probability and OSP amplitudes

Although OSP amplitudes generally decreased with increasing omission probability, the modulation pattern appears to differ between the early components (oN1 and oN2) and the late component (oP3). oN1 and oN2 showed closely aligned modulation patterns: These early OSP components were clearly observed at 10% and 20%, became weak at 30% and 40%, and disappeared at 50% omission. The absence of oN1 and oN2 at 50% omission corresponds with previous studies (Dercksen et al., 2024; SanMiguel et al., 2013b; Stekelenburg and Vroomen, 2015; Tast et al., 2024). The apparent disappearance of oN1 and oN2 does not seem to reflect an abrupt, threshold-like change, but rather a gradual attenuation of prediction error signals, because the difference waveforms still showed a slight but insignificant negative deflection within the oN1 and oN2 time windows.

In the framework of predictive coding, oN1 is thought to reflect a sensory-level prediction error—the discrepancy between an actual activated neural pattern and a preactivated template—whereas oN2 reflects subsequent prediction error processing (Dercksen et al., 2020; Ishida and Nittono, 2025; SanMiguel et al., 2013a; Tast et al., 2024; Tast et al., 2025; van Laarhoven et al., 2017). Their modulation pattern suggests that the magnitude of early omission responses primarily reflects the size of the prediction error, which decreases as omissions become more probable. However, this modulation pattern is not specific to a prediction error account. For example, low-probability omissions may be more salient events that capture attention and enhance ERP amplitudes (e.g., Luck and Kappenman, 2012).

The modulation of oN1 and oN2 showed a stepwise pattern superimposed on an overall linear trend. Overlapping other ERP components could obscure subtle differences across omission probabilities. For example, FRN was observed only for low-probability omissions (10% and 20%), which may have partly contaminated the oN2 amplitude estimates. Although the scalp distributions of the FRN and oN2 differ, it cannot be completely ruled out that FRN-related activity selectively contributed to the enhanced oN2 amplitude observed at lower omission probabilities. Nevertheless, given the close correspondence between the processes thought to be reflected by oN1 and oN2, the highly similar modulation patterns of these two components across omission probabilities support the internal consistency of the present findings.

In contrast, oP3 was reliably observed across all omission probability conditions (10%–50%). Its amplitude declined in a clear linear fashion up to the 40% omission but then reversed (i.e., increased) in the 50% omission, although the difference between the 40% and 50% omissions was not significant. Duncan-Johnson and Donchin (1977) examined P3 amplitudes across stimulus probabilities ranging from 10% to 90% and reported that the P3 amplitude increased as the stimulus probability decreased. Their waveforms and amplitude-probability plots showed that the P3 amplitude decreased from 10% to 40% probability but then increased again at 50%. Although they did not perform statistical comparisons across probabilities, this apparent reversal closely resembles the pattern observed in the present study.

The nonmonotonic modulation of the oP3 amplitude, characterized by a reversal at the 50% omission, cannot be explained solely by the magnitude of the prediction error, which varied monotonically with omission probability in the present study. This dissociation suggests that oP3 may reflect, at least in part, a higher-order process related to evaluating the omission with respect to the broader action–effect mapping. One possible interpretation is that this reversal reflects the context-updating process (Donchin and Coles, 1988; Polich, 2007). At 50% omission (omission trials: 50%, standard trials: 40%, and target trials: 10%), the uncertainty regarding the action–effect mapping was maximal, which may have increased the need to re-evaluate the ongoing stimulus context and action–effect relationship. This requirement may have enhanced oP3 amplitude, consistent with the context updating view of P3. Alternatively, the persistence and nonmonotonic modulation of oP3 could reflect the informational significance of omissions. According to the triarchic model (Johnson, 1986), the amplitude of the P3 (P300) component is determined by subjective probability and stimulus meaning (e.g., stimulus value), scaled by the amount of transmitted information. At 50% omission, omissions may have carried greater value for evaluating the action–effect mapping, thereby sustaining oP3 amplitude.

Together, these findings suggest a possible functional dissociation between early and late OSP components within a predictive-processing framework: oN1 and oN2 appear to reflect earlier stages of prediction error signaling, whereas oP3 may be more closely related to later,

higher-order processes involved in evaluating task-relevant information. Because these interpretations are speculative, further research is needed to disentangle the cognitive processes reflected in different OSP components.

4.3. Behavioral measures

The button-press interval was prolonged in both the omission and target trials compared to the standard trials. This finding is in accordance with Baragona et al. (2025), who reported that unexpected sound omissions capture attention and disrupt an ongoing action plan, thereby prolonging reaction times in a subsequent visual categorization task. These results indicate that transient behavioral changes may be triggered not only by target stimuli that are explicitly task-relevant but also by unexpected omissions. However, the modulation pattern of OSP components by omission probability (Fig. 3) did not correspond to the pattern of the post-omission button-press interval (Fig. 4), which remained largely comparable across omission probability conditions. Together, these findings suggest that post-omission delay may reflect a general disruptive effect—acting as a transient distractor—rather than an adaptive behavioral adjustment that scales with the magnitude of the prediction error indexed by OSP amplitudes.

Trial type also modulated button-press force, which was weaker in the target trials than in the omission and standard trials. Because participants responded to target tones with the opposite hand, they may have released the trigger button earlier. Button-press force did not differ significantly across omission probabilities, although there was a small increase in force with increasing omission probability. Therefore, the probability-dependent modulation of OSP amplitudes mainly reflects neural processes related to predictive processing rather than motor-related activity associated with button presses.

RTs to the target stimulus exhibited an inverted U-shaped pattern as a function of omission probability, with the longest RTs in the 30% omission condition. This trend may reflect flexible strategy adjustment: When targets were rare (80% standard, 10% target), their high salience may have facilitated rapid detection, whereas when targets were relatively likely once a stimulus appeared (40% standard, 10% target), prioritizing rapid responses to stimuli may have been efficient. In contrast, the intermediate 30% omission probability may not have afforded a clear strategy, resulting in longer RTs.

Importantly, these strategic differences did not substantially affect overall task performance. Target hit rates showed only subtle modulation by omission probability, with no significant pairwise differences, and false alarm rates did not differ across conditions. Moreover, the mean button-press intervals did not differ across the probability conditions. Taken together, these findings suggest that the level of task-related arousal (vigilance) was maintained at a comparable level throughout the experiment. Because vigilance is primarily evaluated using accuracy-based measures rather than RT alone (See et al., 1995), the observed RT differences may reflect strategic adjustments rather than changes in vigilance.

5. Limitations

This study had several limitations. First, the cognitive and motor execution processes may have differed between the probability and motor control conditions because the latter did not include the target detection task. The mean button-press interval was longer in the motor control condition ($M = 948$ ms) than in the probability conditions ($M =$ 854–872 ms), consistent with Ishida and Nittono (2025) using a similar omission paradigm. Nevertheless, the button-press intervals did not differ among the probability conditions so the interval differences from the motor control condition can be considered comparable across omission probability levels. Moreover, the button-press force did not differ among the probability conditions or the motor control conditions, indicating that the motor execution of button presses was largely comparable across conditions. These results suggest that differences in button-press behaviors are unlikely to have confounded the comparison of omission-related responses among the probability conditions.

Second, arousal or attentional levels may have varied across the conditions. The number of trials differed substantially across the omission probability conditions because the total number of omission trials was kept constant (e.g., 10%: 1400 trials vs. 50%: 280 trials). To mitigate this, conditions with a larger number of trials (10%–30%) were divided into multiple blocks so that the number of trials per block was comparable across conditions (10%: 350, 20%: 350, 30%: 233, 40%: 350, 50%: 280), and short breaks were provided between blocks. Given that hit rates and false alarm rates did not differ significantly across omission probability conditions, these procedures likely helped maintain a relatively stable level of arousal and attention throughout the experiment.

Third, it remains unclear whether the present findings can be generalized to passive paradigms without self-initiated actions. For example, N2 and P3 are enhanced for self-generated than for externally presented deviant stimuli (Knolle et al., 2013; Nittono, 2006), suggesting that action involvement may affect omission responses. Nevertheless, motor-based predictions have been proposed to represent one of multiple pathways to similar sensory predictions within a general predictive system integrating sensory and motor information (Korka et al., 2021), and comparable omission responses (oN1, oN2, and oP3) have been reported in both action–sensory paradigms (Dercksen et al., 2020, 2022; Korka et al., 2020; SanMiguel et al., 2013a; SanMiguel et al., 2013b; Stekelenburg and Vroomen, 2015) and sensory–sensory paradigms (Stekelenburg and Vroomen, 2015; van Laarhoven et al., 2017). Therefore, although more research is needed to clarify the specific role of the motor system in sensory prediction, similar results are likely to be obtained.

6. Conclusion

The present study demonstrated that the amplitudes of OSPs systematically decreased as omission probability increased, indicating that unexpected and rarer omissions elicited stronger prediction-error responses. The dissociation between early and late OSP components suggests that oN1 and oN2 may index early sensory-level prediction error signaling, whereas oP3 may reflect a later stage in which the representation of the stimulus context is re-evaluated and updated. This provisional functional distinction needs to be examined in future studies. Overall, these findings indicate how the brain dynamically adjusts its predictions under varying degrees of event probability. Based on these results, a practical recommendation for future studies is to use an omission probability of 20% or lower to reliably elicit early OSP components.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, ChatGPT was used for code refinement and English proofreading. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

CRediT authorship contribution statement

Tomomi Ishida: Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – original draft. **Hiroshi Nittono:** Methodology, Conceptualization, Writing – review & editing.

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Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpsycho.2026.113416.

Data availability

The datasets analyzed in this study are available at https://osf.io/nhqrz.

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