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► **To cite this version:**

Álvaro Darriba, Hamdi Habacha, Yang Seok Cho, Florian Waszak. ERP prediction error responses under temporal constraints. *Brain Research*, 2025, 1865, pp.149867. <10.1016/j.brainres.2025.149867>. <hal-05221311>

HAL Id: hal-05221311

<https://hal.science/hal-05221311v1>

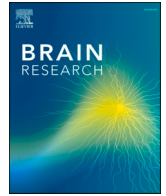
Submitted on 23 Jan 2026

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Research paper

ERP prediction error responses under temporal constraints

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ARTICLE INFO

Keywords:

Prediction
 Processing bottleneck
 Event-related potentials
 N2b
 Temporal constraints

ABSTRACT

Anticipating future events is fundamental to adaptive behaviour. This study used EEG to examine how the brain processes multiple concurrent predictions under time constraints. On each trial, participants heard two auditory cues predicting different features (tilt and spatial frequency) of an upcoming visual stimulus (a Gabor patch), with cues presented either 200 ms or 1000 ms apart. The visual stimulus could either match both predicted features, violate both, or match only one while violating the other. We analysed event-related potentials (ERPs) to the Gabor patch to assess prediction error (PE) responses. Violations of the first cue's prediction consistently elicited robust N2b responses, even when the second cue's prediction was accurate. Violations of both cues produced similarly strong N2b amplitudes, while isolated violations of the second cue had no significant effect. No differences emerged between short and long cue intervals, suggesting that the temporal gap did not modulate PE processing. These results point to a bottleneck in integrating sequential predictions, with earlier cues dominating PE-related EEG responses under temporal constraints.

1. Introduction

Predictive processing refers to the brain's ability to anticipate incoming sensory information on the basis of past experience and contextual cues. This anticipatory mechanism is thought to enable humans to efficiently allocate cognitive resources, anticipate environmental changes, and optimize behavioural responses, by minimizing prediction error (PE), i.e., the mismatch between expected and actual sensory input. While the general framework of predictive processing has been extensively theorized, especially through hierarchical models of Bayesian inference (Friston et al., 2014), how specific predictions are formed and tested remains dependent on the experimental context in which they are studied.

Prior research demonstrates that predictive processing is sensitive to factors such as contextual regularities (Hsu and Hämäläinen, 2021; Tavano et al., 2014; Zinchenko et al., 2018), stimulus complexity (Cappotto et al., 2023; Korka et al., 2019; Lee et al., 2018; Ruiz-Martínez et al., 2021), cognitive load (Ito et al., 2018), and attention (Baker et al., 2021; Jones et al., 2013; Marzecová et al., 2017). In this study, we examine a relatively understudied factor: predictive processing under temporal constraints, focusing on how the timing between multiple predictive cues influences their encoding and the formation of expectations about upcoming sensory events.

While our cognitive system is capable of remarkably complex, parallel processing, limitations when handling multiple streams of information simultaneously or in close temporal proximity are well-established. These information processing bottlenecks can impair our ability to perceive, hold in mind, and act upon stimuli (Marois and Ivanoff, 2005), and can be revealed across a variety of temporal intervals and tasks contexts, whenever multiple cognitive operations compete for limited central resources. Paradigms such as the Rapid Serial Stimulus Presentation and the Psychological Refractory Period (PRP) have been instrumental in exploring these limitations. Rapid serial stimulus presentation paradigms (Potter et al., 2014; Potter and Levy, 1969) involve presenting a sequence of visual or auditory stimuli (RSVP, RASP, respectively) at a rapid rate, usually with a stimulus onset asynchrony (SOA) no greater than 500 ms. Participants are typically required to detect or identify specific target stimuli embedded within this rapid stream. These experiments reveal significant constraints at multiple processing stages, which are modulated by SOA length and other factors such as stimulus characteristics and task demands (Akça et al., 2023; Broadbent and Broadbent, 1987; Dux and Marois, 2009; Evans and Treisman, 2005; Potter et al., 2010, 2002).

Common findings from RSVP studies include errors in recalling the exact order of stimuli (Hilkenmeier et al., 2012; Potter and Levy, 1969), as well as phenomena like repetition blindness (Kanwisher, 1987),

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<https://doi.org/10.1016/j.brainres.2025.149867>

Received 27 December 2024; Received in revised form 31 July 2025; Accepted 2 August 2025

Available online 5 August 2025

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perceptual masking (Enns et al., 2000), and the attentional blink (AB). The AB (Raymond et al., 1992) is perhaps the most widely studied RSVP/RSAP phenomenon. It refers to the difficulty in detecting a second target (T2) when it occurs within 500 ms after a first target (T1) in a rapid stimulus stream (Chun and Potter, 1995; Raymond et al., 1992). This effect is most pronounced in the 200–500 ms window following T1, and attenuates at shorter SOAs. Originally described in the visual modality, AB has also been demonstrated in the auditory domain (Horváth and Burgán, 2011; Shen and Mondor, 2008; Tremblay et al., 2005). This effect suggests that under temporal constraints, the attention deployment to consciously encode an initial target can impair the processing of subsequent stimuli (Nieuwenstein et al., 2009).

In contrast to the AB, where failures to access relevant information are attributed to attentional bottlenecks, the Psychological Refractory Period (PRP) paradigm reveals processing delays even when the information is consciously accessible. In the PRP paradigm (Pashler, 1994; Welford, 1952) participants respond to two stimuli (S1, S2) from two separated, speeded sensorimotor tasks (T1, T2) presented in quick succession, typically a few hundred milliseconds apart. Each stimulus requires a specific response (R1, R2). The key finding is that the response to S2 (R2) progressively increases as the SOA decreases, whereas R1 is relatively unaffected by SOA (Klapp et al., 2019; Pashler, 1994; Tombu and Jolicoeur, 2002).

Unlike the AB, where the second stimulus often fails to reach awareness, PRP findings show that both stimuli are processed and responded to, but that the second response is delayed due to a central processing bottleneck. This delay is interpreted as evidence for the serial nature of decision-making (Dux et al., 2006; Tombu et al., 2011). Together, these paradigms underscore the inherent limitations of cognitive processing under temporal constraints, and have informed a range of theories and models about attentional capacity and serial processing (Dux et al., 2006; Marti et al., 2010; Mittelstädt et al., 2022; Sigman and Dehaene, 2008; Tombu and Jolicoeur, 2003; Zivony and Lamy, 2022). Importantly, in both paradigms, bottlenecks are revealed not merely by stimulus rate, but by capacity limits in serial or overlapping processing stages, which may apply more generally across cognitive domains.

Given the well-documented limitations of cognitive processing under temporal constraints, a compelling question is whether the brain can form and maintain multiple concurrent predictions when the predictive cues are presented under temporal pressure. A short SOA between cues may impair the encoding of the later cue, thereby limiting its contribution to the overall prediction. Alternatively, the brain may still be able to flexibly integrate multiple cues, even when operating under temporal constraints.

We investigated this using event-related potentials (ERPs), which offer millisecond-level temporal resolution, ideal for tracking the dynamic process of prediction formation and PE signalling. A robust finding in the literature is that predicted stimuli elicit attenuated ERP amplitudes, while violations of expectation, i.e., PE, result in larger neural responses. In practical terms, PE manifests as larger ERP amplitude when a prediction is violated compared to when that same prediction is fulfilled. Depending on the particular paradigm employed, these effects have been typically observed across multiple ERP components, including P1, N1, N2b, P3a, and P3b, reflecting different stages of perceptual and cognitive evaluation.

In our study, participants were trained to associate two auditory cues with two visual target features of a Gabor patch: spatial frequency (high or low), and tilt (left or right). Specifically, participants learned through training that one type of auditory cue reliably predicted one of the features of the visual target while the other cue type predicted the other feature. Critically, we manipulated the SOA between the two auditory cues: a short SOA of 200 ms and a long SOA of 1000 ms, to examine how temporal spacing affects the encoding and influence of the second cue. These SOAs were grounded in existing literature: the short SOA falls well within the range in which interference effects due to temporal

constraints are typically observed, while the long SOA was expected to result in significantly reduced or absent interference effects.

While our paradigm differs structurally from classical AB and PRP designs, most notably in using discrete cue-target intervals rather than continuous streams or speeded dual-task responses, the underlying cognitive constraints on prediction formation under temporal pressure are nevertheless highly relevant. To be clear, we do not claim mechanistic equivalence between our task and these paradigms. Rather, we draw on the AB and PRP literatures to motivate our use of inter-cue SOA as a tool for probing capacity limitations in prediction integration, particularly given that bottleneck-related effects are consistently observed at SOAs in the 200–500 ms range.

Each trial thus included two auditory cues followed by a visual target, yielding one of four prediction-outcome combinations: both predictions fulfilled; both predictions violated; first fulfilled, second violated; first violated, second fulfilled. This 2x2 design allowed us to test how violations tied to each cue influenced ERP responses, and how this depended on inter-cue SOA. By manipulating cue timing, we can examine not only whether each cue contributes to the prediction, but also how their temporal spacing interacts with known cognitive bottlenecks and refractory limitations. Specifically, the short SOA condition was expected to produce a functional bottleneck, akin to those observed in AB and PRP paradigms, whereby processing resources are still engaged with the first cue when the second is presented. This limitation may prevent the second cue from being fully encoded, reducing its influence on predictive processing. In contrast, the long SOA condition should minimize such interference, allowing both cues to be processed independently and contribute to the prediction. While our design necessarily involves short-term memory maintenance across the inter-cue SOA, we aimed to test whether impaired prediction integration stemmed from encoding limitations due to temporal constraints, rather than from memory degradation over time.

We consider two main hypotheses:

1. Temporal bottleneck hypothesis: the second cue is not adequately processed due to temporal overlap and refractory limitations in cognitive resources. As a result, only the prediction from the first cue is formed and used to generate a PE signal. In ERP terms, we would expect larger ERP amplitudes only when the first cue's prediction is violated. We hypothesize this to be the most likely scenario in the short-SOA trials. This bottleneck should be attenuated or absent in the long SOA condition, where the cues are temporally separated enough to allow both to be processed without interference.
2. Full processing hypothesis: both cues are adequately processed and contribute to the prediction. We hypothesize this to be the case in long-SOA trials, but unlikely in short-SOA trials. In this case, ERP responses to the target stimulus could reflect:
 - a. Interactive prediction:
 - Conservative: PE arises if either prediction is violated. ERP amplitude increases unless both predictions are fulfilled.
 - Liberal: PE arises only when both predictions are violated. One fulfilled prediction is enough to avoid a strong PE.
 - b. Independent prediction: predictions from each cue are formed and evaluated separately and contribute additively to the PE response. ERP amplitudes would then scale from smallest when both predictions are fulfilled to largest when both are violated, with intermediate values when only one is violated.

2. Materials and Methods

2.1. Participants

A total of 20 healthy volunteers (7 females, mean age = 22.25, age range = 19–26 years) with no history of neurological, neuropsychiatric, or visual/hearing impairments, as indicated by self-report, participated in the experiment. Participants gave written informed consent and

received monetary compensation for their participation. Experimental procedures were undertaken in accordance with the Declaration of Helsinki and with the approval of the Comité de Protection des Personnes Île-de-France II.

2.2. Stimuli and procedures

Stimulus presentation was controlled using Psychtoolbox-3 (Kleiner et al., 2007), running in MATLAB. Auditory cues were delivered through Sennheiser PX200-II headphones at a maximum intensity of 83.3 dB (56–82.7 dBA; 65–83.3 dBC). Visual stimuli (target Gabor patches) were displayed at the centre of a 27-inch, 60 Hz LCD monitor at a viewing distance of 100 cm.

Fig. 1(A) illustrates the trial structure. Each trial began with a central fixation cross displayed for 1500 ms, followed by a sequence of two auditory cues and a visual target (Gabor patch). Each cue was 100 ms in duration. Cues were separated by a variable Stimulus Onset Asynchrony (SOA) of either 200 ms (short SOA) or 1000 ms (long SOA), with both SOAs equally probable and counterbalanced within each block. The visual Gabor patch appeared 300 ms after the onset of the second cue and was presented for 100 ms.

Two types of auditory cues were used, each consistently associated with a specific visual feature (Fig. 1B):

- A binaural sequence of either two or five 440 Hz beeps (within 100 ms) predicted the spatial frequency of the Gabor patch, either low (0.008 cycles/pixel) or high (0.05 cycles/pixel), respectively.
- A single 440 Hz tone (100 ms) presented monaurally to the left or right ear predicted the tilt direction of the Gabor patch, either left or right (tilted 40 degrees from vertical), respectively.

Each trial included both cue types, one predicting spatial frequency and the other predicting tilt. Importantly, the cue type-visual feature mapping was fixed: beep sequences always predicted spatial frequency, and monaural tones always predicted tilt direction.

Notably, the predictive value (cue validity) of each auditory cue

remained fixed at 80 % throughout the experiment. The four cue-target congruency conditions were probabilistically interleaved within blocks, rather than blocked, and arose naturally from this stable validity structure. That is, for example, if the monaural tone was presented to the right ear (predicting a rightward tilt), the Gabor patch was indeed right-tilted on 80 % of those trials and left-tilted on the remaining 20 %; similarly, if the beep sequence indicated high spatial frequency (five beeps), the patch was high-frequency on 80 % of those trials and low-frequency on 20 %. This resulted in four cue-target congruency conditions (Fig. 1C) with the following probabilities:

- Both cues' predictions fulfilled (0.8 x 0.8 = 64 % of trials).
- First cue's prediction fulfilled; second cue's violated (0.8 x 0.2 = 16 % of trials).
- First cue's prediction violated; second cue's fulfilled (0.2 x 0.8 = 16 % of trials).
- Both cue's predictions violated (0.2 x 0.2 = 4 % of trials).

To ensure a well-controlled and counterbalanced design, all cue types (two beeps, five beeps, left monaural tone, right monaural tone) and inter-cue SOAs (200 ms vs. 1000 ms) were presented with equal probability across the experiment. All eight possible combinations of spatial frequency (low, high), tilt (left, right), and inter-cue SOA (200 ms, 1000 ms) (e.g., low-left-200 ms, low-left-1000 ms, etc.) were also presented with equal probability across the task.

Participants completed 12 blocks of 200 trials each. In 6 blocks, the first cue always predicted spatial frequency (i.e., it was a binaural sequence of beeps); in the other 6, the first cue always predicted tilt (i.e., it was a monaurally presented tone). The sequence of block types was fully counterbalanced across participants. Trial sequences were pseudorandomized within each block to maintain the intended condition balance while avoiding stimulus repetition effects.

Before the EEG recording, participants completed 30 structured practice trials with feedback. During this phase, they were explicitly instructed to use the auditory cues to form predictions about the visual targets. The practice ensured that participants correctly understood the

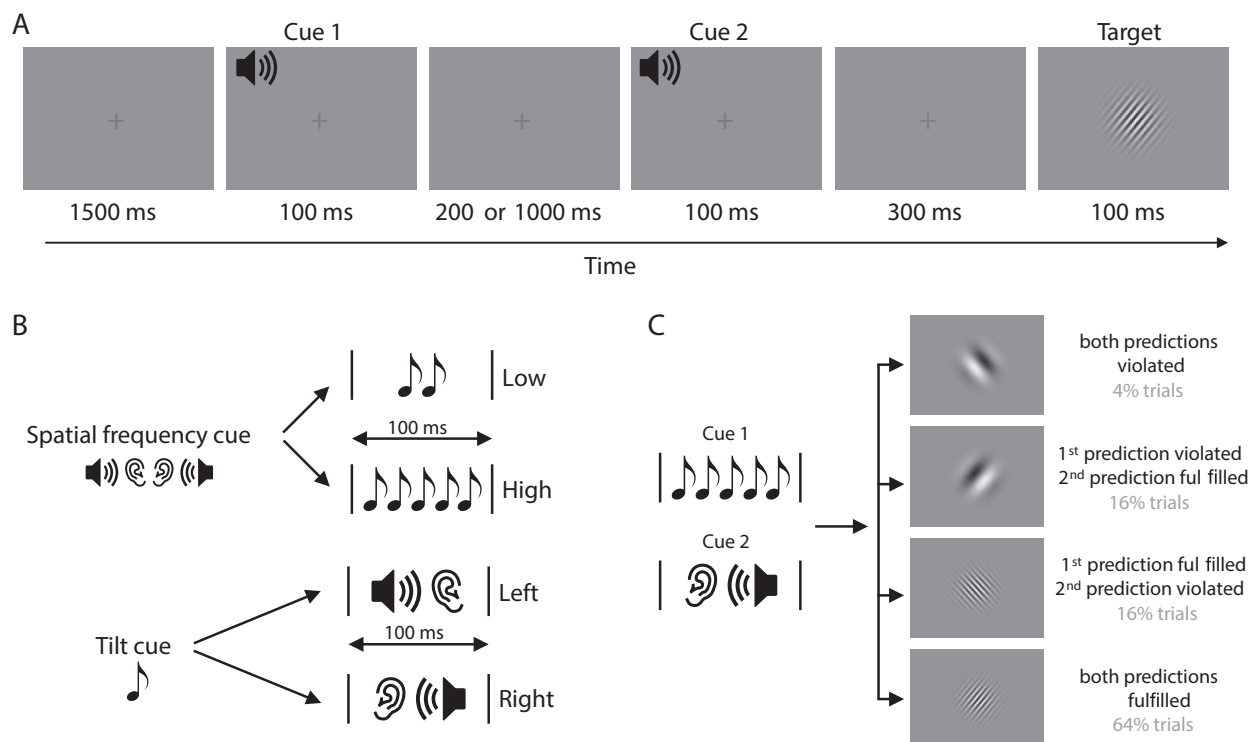


Fig. 1. Description of the experimental setup.

fixed cue-feature mappings and could perceive and interpret the stimuli. Only after confirming adequate understanding and performance did the experimental session begin.

To help maintain focus throughout the experimental task, 20 catch trials were randomly interspersed within each block. On these trials, participants were prompted with on-screen questions, asking either “Is the orientation as expected?” or “Is the spatial frequency as expected?”. Participants responded by pressing either the left or right key on a response pad. The primary purpose of these catch trials was to maintain attentiveness, and reduce mind-wandering, by intermittently requiring active responses (Langner et al., 2010). These trials were not intended to assess learning of cue-feature mappings, which was confirmed during practice, but rather to ensure sustained attention during the main experiment.

2.3. EEG data acquisition and preprocessing

We recorded the EEG using the PyCorder system and actiCHamp amplifiers (BrainProducts GmbH, Gilching, Germany) in DC mode with a sampling rate of 2000 Hz. Continuous EEG data were collected from 60 actiCAP EEG electrodes (BrainProducts GmbH) mounted on an elastic cap and referenced to right mastoid. EEG electrodes were arranged following the extended 10–10 position system (Acharya et al., 2016). Additional electrodes were placed on the left mastoid and on the outer canthi of both eyes. EEG data were processed using custom-built scripts using EEGLAB v2024.0 (Delorme and Makeig, 2004) functions running under MATLAB R2020a (Mathworks, Navick, MA). The EEG data was filtered offline (high pass: 0.1 Hz, low pass: 40 Hz), and re-referenced to linked mastoids. Bad channels were identified by visual inspection of the EEG raw data and the channels’ power spectra, and excluded from processing (M = 2.55 channels, SD = 1.85; 4.25 % of electrodes).

Epochs were extracted from – 200 ms to + 600 ms relative to target onset and baselines were corrected to the 200 ms pre-target interval. Since Cue 2 occurred 300 ms prior to target onset, this baseline window could contain some residual Cue 2-related activity. However, Cue 2 identity was fully counterbalanced across conditions and inter-cue SOAs ensuring that any such residual activity was equally distributed across experimental conditions. Thus, potential cue-related baseline activity would not introduce systematic bias in condition comparisons. Visual inspection of ERP plots confirmed that baseline activity did not differ across conditions.

Stereotyped artifacts, including blinks and eye movements, were deleted via independent component analysis (ICA) using the extended infomax algorithm (Bell and Sejnowski, 1995). The remaining

components were then projected back into electrode space. Subsequently, we removed all trials in which activity exceeded $\pm 100 \mu\text{V}$ to account for noise and large muscle artefacts. The average number of trials retained after artifact rejection was 2264.75 (94.36 % of trials, SD = 17.31). Channels that were deemed bad were reintroduced by interpolating data between neighbouring electrodes using spherical spline interpolation (Perrin et al., 1987).

2.4. ERP analyses

ERP average waveforms were computed for each Condition (both predictions fulfilled; first prediction fulfilled and second prediction violated; first prediction violated and second prediction fulfilled; both predictions violated) and inter-cue SOA (200 ms; 1000 ms), separately. To minimize inter-individual variability in scalp topographies and reduce the number of statistical comparisons, ERP analyses were conducted using predefined regions of interest (ROIs), each comprising a pair of electrodes. These ROIs were selected based on grand-average waveforms and topographical maps (Fig. 2). Following this procedure, visual sensory responses were measured at lateral parieto-occipital sites (PO7, PO8; P1: 92–112 ms; N1: 158–178 ms), frontal components at a frontocentral ROI (Fz, FCz), including N2b (252–272 ms) and P3a (310–330 ms), while the P3b component was measured at a parieto-occipital ROI (Pz, POz; 375–425 ms).

To evaluate the effects of Condition and SOA on ERP amplitudes, we employed Bayesian linear mixed models (LMMs), which offer greater flexibility and statistical power than traditional repeated-measures ANOVA. Although grand-average waveforms are shown for visualization, all statistical analyses were performed on single-trial amplitudes, extracted as the mean voltage within fixed time windows centred on each component’s peak as identified in the grand-average waveform.

LMMs were implemented using the brms package (Bürkner, 2017), a high-level interface to Stan (Carpenter et al., 2017) in R (RCore, 2016). Data visualization was performed using brms and ggplot2 (Wickham, 2016). For each ERP component, the model included fixed effects of Condition (four levels), SOA (two levels), and their interaction, as well as random intercepts and slopes for each participant to account for individual differences in baseline amplitudes and effect sizes (Barr et al., 2013). This approach enabled us to capture both population-level effects of interest and subject-level variability. Categorical contrasts were centred using sum contrasts (Baayen, 2008), so the model intercept represents the grand mean.

All ERP components had normally distributed amplitudes and did not require transformation (Baayen and Milin, 2010). Weakly

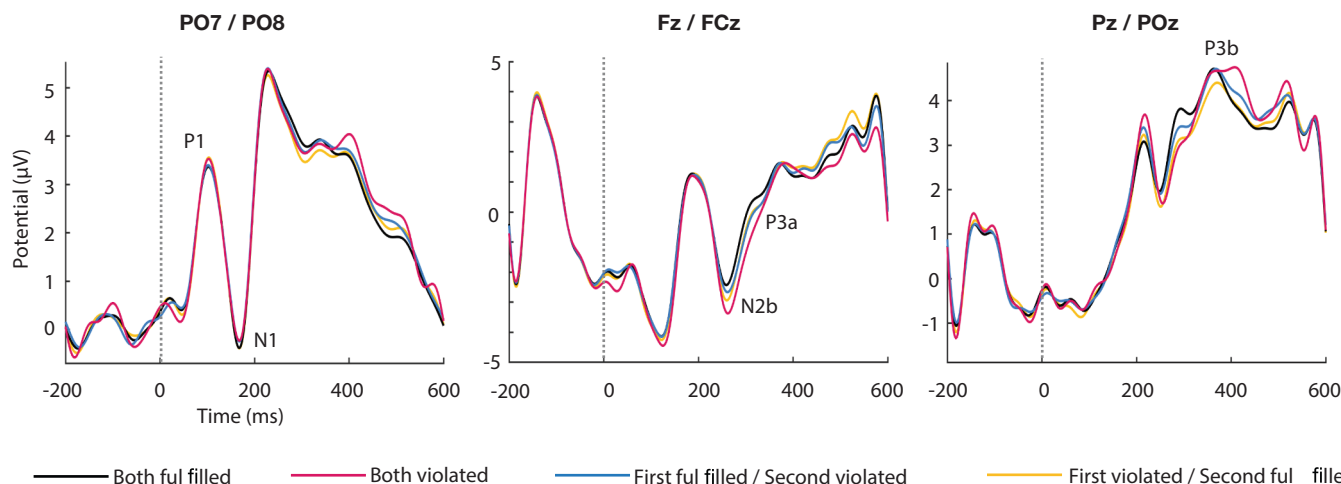


Fig. 2. ERP grand-averages waveforms from the lateral parieto-occipital (PO7, PO8), fronto-central (Fz, FCz), and parieto-occipital (Pz, POz) electrodes, showing the P1, N1, N2b, P3a, and P3b components compared across validity conditions.

informative priors (normal, mean = 0, SD = 1) were used for fixed effects, while all other priors remained at default settings. Models were estimated using four chains of 2000 iterations each (1000 warm-up), with a maximum tree depth of 15, and a target acceptance rate (adapt_delta) of 0.95. Convergence was confirmed via visual inspection of trace plots and Rhat values equal to 1.00 for all parameters. Coefficient estimates are reported as 95 % credible intervals, reflecting the probability that the parameter lies within that interval.

Each ERP component was modelled with the following formula:

‘brm (formula: Amplitude~Condition*SOA+(1 + Condition*SOA | Participant))’.

3. Results

3.1. Behavioural results

Participants reported the stimulus feature they were asked about as matching their expectations in 89.75 % (SD = 4.13) of the catch trials, indicating their active engagement with the task.

3.2. ERP results

All the stimuli evoked the canonical P1, N1, N2b, P3a, and P3b components, with P3a being considerably weak relative to the other components.

The results obtained in the statistical analyses are graphically illustrated in Fig. 3. Only the analysis of N2b yielded any significant effect. This analysis revealed significantly larger amplitudes in the “Both predictions violated” and “First prediction violated / Second prediction fulfilled” conditions compared to the “Both predictions fulfilled condition”, with no significant effects of SOA and no interaction of SOA with any validity condition.

4. Discussion

In this study, we explored participants’ ability to form predictions based on sensory information presented under temporal constraints, using EEG to track their neural responses to violations of those predictions. The task involved two auditory cues presented in succession, each probabilistically predicting a distinct feature of an upcoming visual target. Our results largely support Hypothesis 1: violations of the first cue’s prediction elicited robust PE responses, as reflected by enhanced N2b amplitudes. This effect occurred regardless of whether the second cue’s prediction was also violated and was not modulated by SOA, suggesting that the first cue exerted a dominant influence on prediction formation. Contrary to Hypothesis 2, we found no evidence that increased temporal separation between cues facilitated integration of both predictions. These findings underscore the brain’s processing capacity limitations when operating under temporal constraints in a predictive context.

The N2b effect was the most reliable index of PE in our task, showing increased amplitude following violations of the first cue’s prediction. Frontal negativities peaking 200–300 ms after stimulus onset have been associated with detecting mismatches between expected and actual outcomes in various cognitive tasks, including action selection (control-related N2), attention (mismatch or novelty N2, or N2b), and reward prediction (feedback related negativity) (Folstein and Petten, 2008). Since all these components have been associated with the anterior cingulate cortex (ACC) function (Crottaz-Herbette and Menon, 2006; Nieuwenhuis et al., 2003; Walsh and Anderson, 2012), it has been argued that they may reflect the involvement of the ACC in error detection and adaptation to different contextual demands (Cavanagh et al., 2010). The amplitude of the frontocentral N2b has been observed to increase in response to the detection, under attention conditions, of novelty or mismatch from an expected or predicted sensory input (Ferdinand et al., 2008; Knolle et al., 2013). Therefore, the amplitude increase of N2b observed here provides evidence that participants successfully processed the first cue and that the violation of its associated prediction triggered a PE response. Importantly, this increase in N2b amplitude was consistent regardless of whether the second cue’s

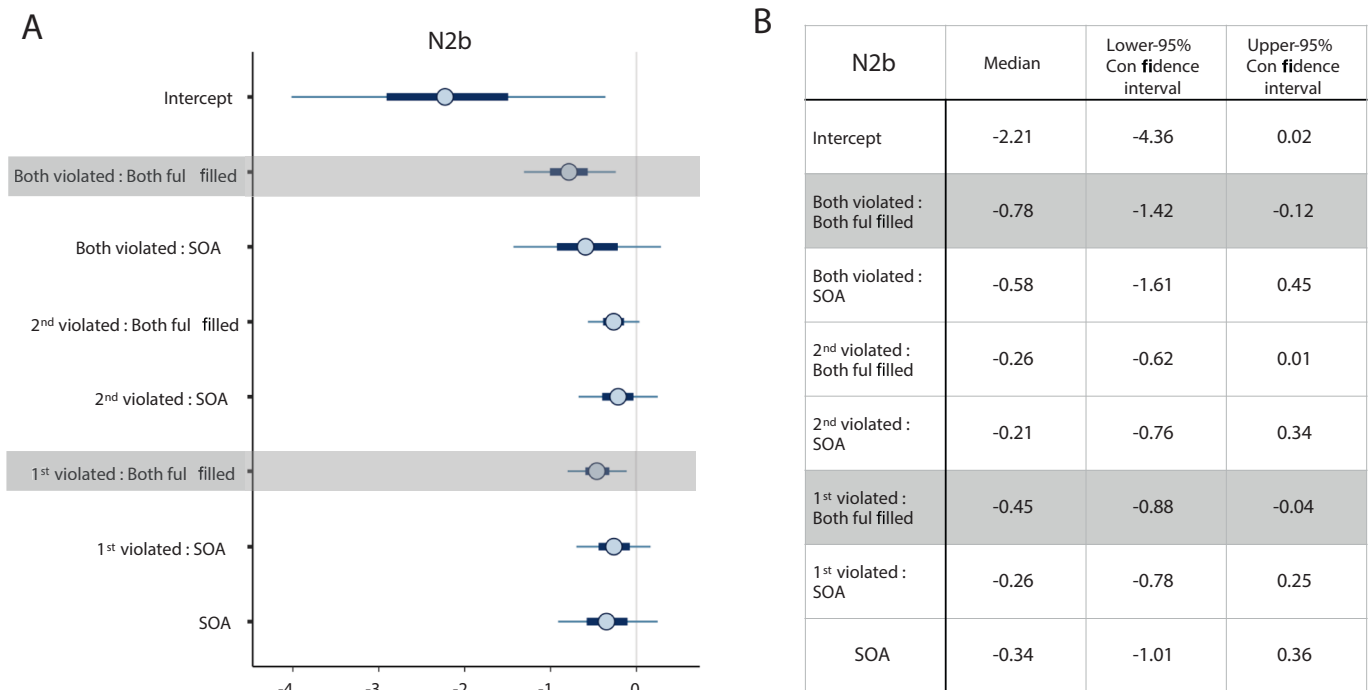


Fig. 3. Medians and credible intervals of parameter values in N2b (On the plot [A]: 50% thick line; 90% thin line. On the table [B]:95%). Intervals that do not include zero have the denoted probability to be a true effect. Significant results are shaded in grey.

prediction was also violated, indicating that the second cue did not significantly contribute to prediction formation.

Critically, the second cue did not elicit comparable effects. Prediction violations based on the second cue failed to modulate N2b amplitude, and this was true even when the SOA was long (1000 ms). This finding suggests that the second cue was either insufficiently processed to inform predictions or that any prediction it supported did not contribute to early PE detection. Notably, we observed no main effects of SOA or interactions between SOA and prediction validity, indicating that simply increasing the interval between cues was not sufficient to overcome the observed processing limitation. One possible explanation is that attentional resources were largely allocated to the first cue, leaving insufficient capacity to fully process the second, particularly in the short SOA condition (200 ms). This is reminiscent of the AB phenomenon (Raymond et al., 1992), where the processing of a second target is impaired when it follows the first closely in time. However, since AB is typically observed when the second target appears within 200–500 ms after the first, but dissipates beyond that range (Martens and Wyble, 2010), it seems unlikely that a similar effect would impair the perception of the second cue in the long SOA trials (1000 ms).

A more plausible explanation lies in capacity-limited models of conscious processing, which posit the existence of a central bottleneck that constrains the serial integration of information into working memory and conscious awareness (Marti et al., 2012; Tombu et al., 2011). According to these models, while early sensory processes are largely unconscious and can occur in parallel as soon as stimuli are presented, subsequent higher-order processes related to conscious access are strictly serial, and subject to a later central, amodal information processing bottleneck (Dehaene and Changeux, 2011; Sigman and Dehaene, 2008). Within this framework, the second cue may have been presented while this central system was still occupied processing the first, resulting in delayed or incomplete encoding of the second cue. Consequently, its predictive content may have been unavailable in time to influence PE signals elicited by the visual stimulus. The lack of an SOA effect suggests that this bottleneck is not simply overcome by longer intervals, potentially because the time needed to process the first cue exceeded the temporal availability or representational fidelity of the second cue in memory. This bottleneck may involve both attentional and memory-related constraints, and future research should explore their relative contributions more precisely.

It is important to distinguish this type of bottleneck from the central processing limitations studied in paradigms such as the PRP, where speeded motor responses to two tasks are delayed due to interference at the response selection stage (Pashler, 1994). Our task did not involve speeded responses, nor did it require participants to act upon the cues directly. Instead, participants engaged in perceptual inference based on arbitrary, probabilistic associations between auditory cues and visual features. This setup more closely resembles tasks involving high cognitive load and rule-based integration, where conscious access and attentional resources are required for effective processing. Under such conditions, central bottlenecks may reflect limitations in the system's ability to serially integrate complex or arbitrary associations, rather than constraints at the motor output level.

The explanation we propose for the observed results hinges on the involvement of attention and the necessity of conscious access to the cues in generating predictions and detecting PE when those predictions are violated. While automatic PE detection, in the absence of attention and awareness, is well-documented in predictive processing literature (Friston, 2005; Garrido et al., 2009; Kok et al., 2012; Wacongne et al., 2012), and ERP responses such as the N400, often considered as indexing PE (Kutas and Federmeier, 2011) can persist even under conditions of attentional interference like the PRP or the AB (Vachon and Jolicœur, 2011; Vogel et al., 1998), such automatic detection typically arises in environments with strong contextual regularities, where the brain can easily form predictions based on repetitive or predictable patterns and detect a simple mismatch (as in the case of oddball or

mismatch negativity paradigms), or in contexts where the brain can form strong expectations based on pre-existing semantic networks or real-world knowledge (as in the case of the N400).

In contrast, the present experiment tasked participants with processing two auditory cues in quick succession to predict two different features of an upcoming visual stimulus. These associations were neither intuitive nor based on sensory regularities or prior knowledge. Instead, they were arbitrary and probabilistic, requiring participants to consciously learn, maintain, and apply them. This setup likely imposed a substantial cognitive load, increasing reliance on controlled, top-down processing mechanisms rather than automatic, bottom-up ones. As a result, the predictive system may have been more susceptible to central processing limitations. While it remains possible that the second cue was processed at a low sensory level, this may not have sufficed to support full prediction formation or to generate a PE signal upon violation. The higher-order mechanisms required for consciously mediated prediction and PE detection, reflected in components like the N2b, may have been blocked or delayed by the central bottleneck. This would account for the absence of a second-cue violation effect in the N2b response.

In line with this interpretation, we found no significant effects in early ERP components (P1, N1) which typically reflect automatic sensory processing and may be modulated by strong, consistent expectations (Bendixen et al., 2012). Similarly, neither the P3a nor P3b components were significantly modulated by prediction violations. P3a is typically described as an index of PE, with its amplitude increasing in response to surprising or unpredicted stimuli (Nieuwenhuis et al., 2011). This “surprise” signal is strongly influenced by the saliency and predictability of the eliciting stimulus (Mars et al., 2008). In the present experiment, participants were actively engaged in using top-down processes to make deliberate predictions based on auditory cues. This top-down focus might have suppressed the automatic attention orienting response typically associated with P3a, as participants were likely anticipating valid and invalid trials. In situations where participants are actively directing attention to specific features or are expecting PE, P3a responses are often diminished or absent (Friedman et al., 2001). Regarding P3b, it is thought to reflect a higher-order stage in the PE processing, associated with the conscious recognition of prediction violations and the subsequent updating of internal models (Polich, 2007; Wacongne et al., 2011). The absence of significant P3b effects may indicate that, although violations were detected, as indicated by the effects on N2b, these violations did not place strong enough demands on participants to re-evaluate or update their expectations after a violation. Given that prediction violations were relatively frequent ($p = 0.36$), participants may have anticipated them, reducing the need for updating of expectations, thereby eliminating any differences in P3b amplitude across conditions. Additionally, because participants were not required to make explicit decisions or take actions based on these violations, there may have been less cognitive engagement in updating their internal models, further contributing to the lack of P3b differences across conditions.

As detailed in the Methods section, the task differed from passive paradigms that rely on automatic predictions from sensory regularities, as it required participants to actively learn and apply arbitrary cue-feature associations. This demanded sustained top-down control and continuous internal processing with minimal overt behaviour over an extended period of time. To help maintain attentional engagement and reduce mind-wandering under these cognitively demanding conditions, we pragmatically incorporated intermittent response catch trials. Although these were not explicitly designed as attentional re-alerting interventions (Langner et al., 2010), they may have incidentally fulfilled this role, aligning to some extent with task alternation models (Schumann et al., 2022).

Several limitations of the present study should be acknowledged, as they may affect the interpretation of the results, particularly the absence of ERP modulations related to second-cue violations and the lack of SOA effects. Two main factors could account for these findings. First, the

results obtained may reflect strategic prioritization by participants rather than the influence of a cognitive bottleneck. Given the high cognitive demands and complexity of the task, participants might have chosen, consciously or unconsciously, to focus on the first cue at the expense of the second. Although this explanation appears less likely, as participants received explicit instructions and training to attend to both cues, the study did not include measures of participants' subjective experience regarding prediction formation or violation. Additionally, ERP responses to the cues themselves were not recorded, leaving uncertainty about how deeply the second cue was processed and whether its influence was modulated by participant strategy or by structural processing constraints. Second, the short interval between the second cue and the visual stimulus may have limited participants' ability to form or apply predictions based on this cue. It is possible that its processing was interrupted or overlapped with the processing of the visual stimulus and its comparison to the first cue's prediction, preventing the formation of a precise expectation. Alternatively, even if the second cue was processed, this processing may have been completed too late to influence the N2b response to the visual stimulus. In either scenario, any potential SOA effect would be eliminated, and the ERP response to the visual stimulus would not show evidence of PE when the second cue's prediction was violated.

Finally, the relatively small sample size may constrain the statistical power and generalizability of the findings. While the sample size is consistent with previous EEG research, future studies should aim to replicate and extend these results using larger and more diverse samples, as well as alternative designs that vary cue timing and complexity. Additionally, future research should manipulate memory load or attentional demands independently to disentangle their relative contributions to the observed effects. Other promising directions include probing the temporal dynamics of second-cue processing more precisely or adapting task structures to minimize strategic prioritization. Together, these approaches could help clarify the boundary conditions under which parallel prediction processing becomes feasible under temporal constraints.

5. Conclusion

This study provides new insights into the limitations of predictive processing under temporal constraints, offering evidence for a central bottleneck that affects the processing of sequential predictions. The findings support Hypothesis 1: under both short and long SOA conditions, participants primarily relied on the first cue to generate predictions. This was reflected in robust N2b responses to violations of the first cue, with no detectable contribution from the second.

In contrast, Hypothesis 2, predicting full processing of both cues in the long-SOA condition, was not supported. Even when more time was available between cues, violations of the second cue did not elicit significant error-related ERP responses. This suggests that cognitive resources remained focused on the first cue and that the second cue was not fully integrated into the PE computation. The absence of additive or interactive effects between the two cues further supports the notion of a central processing bottleneck, limiting the cognitive system's capacity to process multiple sequential predictions concurrently.

Overall, these results highlight the limitations of predictive processing under temporal constraints, indicating that when cognitive resources are taxed, the brain tends to prioritize early information, even when more time is available for additional processing.

CRedit authorship contribution statement

Álvaro Darriba: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Hamdi Habacha:** Methodology, Investigation, Conceptualization. **Yang Seok Cho:** Writing – review & editing, Conceptualization. **Florian Waszak:** Writing – review & editing, Supervision, Project

administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was partly supported by IdEx Université Paris Cité ANR-18-IDEX-0001.

Data availability

Data will be made available on request.

References

- Acharya, J.N., Hani, A.J., Thirumala, P.D., Tsuchida, T.N., 2016. American Clinical Neurophysiology Society Guideline 3: A Proposal for Standard Montages to Be Used in Clinical EEG. *J. Clin. Neurophysiol. Off. Publ. Am. Electroencephalogr. Soc.* 33, 312–316. <https://doi.org/10.1097/WNP.0000000000000317>.
- Akça, M., Bishop, L., Vuoskoski, J.K., Laeng, B., 2023. Human voices escape the auditory attentional blink: Evidence from detections and pupil responses. *Brain Cogn.* 165, 105928. <https://doi.org/10.1016/j.bandc.2022.105928>.
- Baayen, R.H., 2008. *Analyzing Linguistic Data: A Practical Introduction to Statistics using R*. Cambridge University Press, Cambridge. <https://doi.org/10.1017/CBO9780511801686>.
- Baayen, R.H., Milin, P., 2010. Analyzing reaction times. <https://doi.org/10.21500/20112084.807>.
- Baker, K.S., Pegna, A.J., Yamamoto, N., Johnston, P., 2021. Attention and prediction modulations in expected and unexpected visuospatial trajectories. *PLoS One* 16, e0242753. <https://doi.org/10.1371/journal.pone.0242753>.
- Barr, D.J., Levy, R., Scheepers, C., Tily, H.J., 2013. Random effects structure for confirmatory hypothesis testing: Keep it maximal. *J. Mem. Lang.* 68, 255–278. <https://doi.org/10.1016/j.jml.2012.11.001>.
- Bell, A.J., Sejnowski, T.J., 1995. An information-maximization approach to blind separation and blind deconvolution. *Neural Comput.* 7, 1129–1159. <https://doi.org/10.1162/neco.1995.7.6.1129>.
- Bendixen, A., SanMiguel, I., Schröger, E., 2012. Early electrophysiological indicators for predictive processing in audition: a review. *Int. J. Psychophysiol. Off. J. Int. Organ. Psychophysiol.* 83, 120–131. <https://doi.org/10.1016/j.ijpsycho.2011.08.003>.
- Broadbent, D.E., Broadbent, M.H., 1987. From detection to identification: response to multiple targets in rapid serial visual presentation. *Percept. Psychophys.* 42, 105–113. <https://doi.org/10.3758/bf03210498>.
- Bürkner, P.-C., 2017. brms: An R Package for Bayesian Multilevel Models Using Stan. *J. Stat. Softw.* 80, 1–28. <https://doi.org/10.18637/jss.v080.i01>.
- Cappotto, D., Luo, D., Lai, H.W., Peng, F., Melloni, L., Schnupp, J.W.H., Auksztulewicz, R., 2023. “What” and “when” predictions modulate auditory processing in a mutually congruent manner. *Front. Neurosci.* 17, 1180066. <https://doi.org/10.3389/fnins.2023.1180066>.
- Carpenter, B., Gelman, A., Hoffman, M.D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., Riddell, A., 2017. Stan: A Probabilistic Programming Language. *J. Stat. Softw.* 76, 1–32. <https://doi.org/10.18637/jss.v076.i01>.
- Cavanagh, J.F., Frank, M.J., Klein, T.J., Allen, J.J.B., 2010. Frontal theta links prediction errors to behavioral adaptation in reinforcement learning. *NeuroImage* 49, 3198–3209. <https://doi.org/10.1016/j.neuroimage.2009.11.080>.
- Chun, M.M., Potter, M.C., 1995. A two-stage model for multiple target detection in rapid serial visual presentation. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 109–127. <https://doi.org/10.1037//0096-1523.21.1.109>.
- Crottaz-Herbette, S., Menon, V., 2006. Where and when the anterior cingulate cortex modulates attentional response: combined fMRI and ERP evidence. *J. Cogn. Neurosci.* 18, 766–780. <https://doi.org/10.1162/jocn.2006.18.5.766>.
- Dehaene, S., Changeux, J.-P., 2011. Experimental and Theoretical Approaches to Conscious Processing. *Neuron* 70, 200–227. <https://doi.org/10.1016/j.neuron.2011.03.018>.
- Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>.
- Dux, P.E., Ivanoff, J., Asplund, C.L., Marois, R., 2006. Isolation of a Central Bottleneck of Information Processing with Time-Resolved fMRI. *Neuron* 52, 1109–1120. <https://doi.org/10.1016/j.neuron.2006.11.009>.
- Dux, P.E., Marois, R., 2009. How humans search for targets through time: A review of data and theory from the attentional blink. *Atten. Percept. Psychophys.* 71, 1683–1700. <https://doi.org/10.3758/APP.71.8.1683>.
- Enns, J.T., Lollo, V.D., Enns, J.T., Lollo, V.D., 2000. What's new in visual masking? *Trends Cogn. Sci.* 4, 345–352. [https://doi.org/10.1016/S1364-6613\(00\)01520-5](https://doi.org/10.1016/S1364-6613(00)01520-5).

- Evans, K.K., Treisman, A., 2005. Perception of objects in natural scenes: is it really attention free? *J. Exp. Psychol. Hum. Percept. Perform.* 31, 1476–1492. <https://doi.org/10.1037/0096-1523.31.6.1476>.
- Ferdinand, N.K., Mecklinger, A., Kray, J., 2008. Error and Deviance Processing in Implicit and Explicit Sequence Learning. *J. Cogn. Neurosci.* 20, 629–642. <https://doi.org/10.1162/jocn.2008.20046>.
- Folstein, J.R., Petten, C.V., 2008. Influence of cognitive control and mismatch on the N2 component of the ERP: A review. *Psychophysiology* 45, 152–170. <https://doi.org/10.1111/j.1469-8986.2007.00602.x>.
- Friedman, D., Cycowicz, Y.M., Gaeta, H., 2001. The novelty P3: an event-related brain potential (ERP) sign of the brain's evaluation of novelty. *Neurosci. Biobehav. Rev.* 25, 355–373. [https://doi.org/10.1016/S0149-7634\(01\)00019-7](https://doi.org/10.1016/S0149-7634(01)00019-7).
- Friston, K., 2005. A theory of cortical responses. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 360, 815–836. <https://doi.org/10.1098/rstb.2005.1622>.
- Friston, K.J., Stephan, K.E., Montague, R., Dolan, R.J., 2014. Computational psychiatry: the brain as a phantastic organ. *Lancet Psychiatry* 1, 148–158. [https://doi.org/10.1016/S2215-0366\(14\)70275-5](https://doi.org/10.1016/S2215-0366(14)70275-5).
- Garrido, M.I., Kilner, J.M., Stephan, K.E., Friston, K.J., 2009. The mismatch negativity: a review of underlying mechanisms. *Clin. Neurophysiol. Off. J. Int. Fed. Clin. Neurophysiol.* 120, 453–463. <https://doi.org/10.1016/j.clinph.2008.11.029>.
- Hilkenmeier, F., Olivers, C.N.L., Scharlau, I., 2012. Prior entry and temporal attention: Cueing affects order errors in RSVP. *J. Exp. Psychol. Hum. Percept. Perform.* 38, 180–190. <https://doi.org/10.1037/a0025978>.
- Horváth, B., Burgián, A., 2011. Distraction and the auditory attentional blink. *Atten. Percept. Psychophys.* 73, 695–701. <https://doi.org/10.3758/s13414-010-0077-3>.
- Hsu, Y.-F., Hämäläinen, J.A., 2021. Both contextual regularity and selective attention affect the reduction of precision-weighted prediction errors but in distinct manners. *Psychophysiology* 58, e13753. <https://doi.org/10.1111/psyp.13753>.
- Ito, A., Corley, M., Pickering, M.J., 2018. A cognitive load delays predictive eye movements similarly during L1 and L2 comprehension. *Biling. Lang. Cogn.* 21, 251–264. <https://doi.org/10.1017/S1366728917000050>.
- Jones, A., Hughes, G., Waszak, F., 2013. The interaction between attention and motor prediction. An ERP study. *NeuroImage* 83, 533–541. <https://doi.org/10.1016/j.neuroimage.2013.07.004>.
- Kanwisher, N.G., 1987. Repetition blindness: type recognition without token individuation. *Cognition* 27, 117–143. [https://doi.org/10.1016/0010-0277\(87\)90016-3](https://doi.org/10.1016/0010-0277(87)90016-3).
- Klapp, S.T., Maslovat, D., Jagacinski, R.J., 2019. The bottleneck of the psychological refractory period effect involves timing of response initiation rather than response selection. *Psychon. Bull. Rev.* 26, 29–47. <https://doi.org/10.3758/s13423-018-1498-6>.
- Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., Broussard, C., 2007. What's new in psychtoolbox-3. *Perception* 36, 1–16.
- Knolle, F., Schröger, E., Kotz, S.A., 2013. Prediction errors in self- and externally-generated deviants. *Biol. Psychol.* 92, 410–416. <https://doi.org/10.1016/j.biopsycho.2012.11.017>.
- 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. *Cereb. Cortex N. Y. N 1991* (22), 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? *J. Cogn. Neurosci.* 31, 1917–1932. https://doi.org/10.1162/jocn_a.01456.
- Kutas, M., Federmeier, K.D., 2011. Thirty years and counting: Finding meaning in the N400 component of the event related brain potential (ERP). *Annu. Rev. Psychol.* 62, 621–647. <https://doi.org/10.1146/annurev.psych.093008.131123>.
- Langner, R., Steinborn, M.B., Chatterjee, A., Sturm, W., Willmes, K., 2010. Mental fatigue and temporal preparation in simple reaction-time performance. *Acta Psychol.* (Amst.) 133, 64–72. <https://doi.org/10.1016/j.actpsy.2009.10.001>.
- Lee, K., Oh, Y., Izawa, J., Schweighofer, N., 2018. Sensory prediction errors, not performance errors, update memories in visuomotor adaptation. *Sci. Rep.* 8, 16483. <https://doi.org/10.1038/s41598-018-34598-y>.
- Marois, R., Ivanoff, J., 2005. Capacity limits of information processing in the brain. *Trends Cogn. Sci.* 9, 296–305. <https://doi.org/10.1016/j.tics.2005.04.010>.
- Mars, R.B., Debener, S., Gladwin, T.E., Harrison, L.M., Haggard, P., Rothwell, J.C., Bestmann, S., 2008. Trial-by-Trial Fluctuations in the Event-Related Electroencephalogram Reflect Dynamic Changes in the Degree of Surprise. *J. Neurosci.* 28, 12539–12545. <https://doi.org/10.1523/JNEUROSCI.2925-08.2008>.
- Martens, S., Wyble, B., 2010. The attentional blink: Past, present, and future of a blind spot in perceptual awareness. *Neurosci. Biobehav. Rev.*, Special Section: Developmental determinants of sensitivity and resistance to stress: A tribute to Seymour "Gig" Levine 34, 947–957. <https://doi.org/10.1016/j.neubiorev.2009.12.005>.
- Marti, S., Sackur, J., Sigman, M., Dehaene, S., 2010. Mapping introspection's blind spot: reconstruction of dual-task phenomenology using quantified introspection. *Cognition* 115, 303–313. <https://doi.org/10.1016/j.cognition.2010.01.003>.
- Marti, S., Sigman, M., Dehaene, S., 2012. A shared cortical bottleneck underlying Attentional Blink and Psychological Refractory Period. *NeuroImage* 59, 2883–2898. <https://doi.org/10.1016/j.neuroimage.2011.09.063>.
- Marzecová, A., Widmann, A., SanMiguel, I., Kotz, S.A., Schröger, E., 2017. Interrelation of attention and prediction in visual processing: Effects of task-relevance and stimulus probability. *Biol. Psychol.* 125, 76–90. <https://doi.org/10.1016/j.biopsycho.2017.02.009>.
- Mittelstädt, V., Mackenzie, I.G., Miller, J., 2022. Evidence of resource sharing in the psychological refractory period (PRP) paradigm. *J. Exp. Psychol. Hum. Percept. Perform.* 48, 1279–1293. <https://doi.org/10.1037/xhp0001052>.
- Nieuwenhuis, S., De Geus, E.J., Aston-Jones, G., 2011. The anatomical and functional relationship between the P3 and autonomic components of the orienting response. *Psychophysiology* 48, 162–175. <https://doi.org/10.1111/j.1469-8986.2010.01057.x>.
- Nieuwenhuis, S., Yeung, N., van den Wildenberg, W., Ridderinkhof, K.R., 2003. Electrophysiological correlates of anterior cingulate function in a go/no-go task: effects of response conflict and trial type frequency. *Cogn. Affect. Behav. Neurosci.* 3, 17–26. <https://doi.org/10.3758/cabn.3.1.17>.
- Nieuwenstein, M., Van der Burg, E., Theeuwes, J., Wyble, B., Potter, M., 2009. Temporal constraints on conscious vision: on the ubiquitous nature of the attentional blink. *J. Vis.* 9 (18), 1–14. <https://doi.org/10.1167/9.9.18>.
- Pashler, H., 1994. Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244. <https://doi.org/10.1037/0033-2909.116.2.220>.
- Perrin, F., Pernier, J., Bertrand, O., Giard, M.H., Echallier, J.F., 1987. Mapping of scalp potentials by surface spline interpolation. *Electroencephalogr. Clin. Neurophysiol.* 66, 75–81. [https://doi.org/10.1016/0013-4694\(87\)90141-6](https://doi.org/10.1016/0013-4694(87)90141-6).
- Polich, J., 2007. Updating P300: An Integrative Theory of P3a and P3b. *Clin. Neurophysiol. Off. J. Int. Fed. Clin. Neurophysiol.* 118, 2128–2148. <https://doi.org/10.1016/j.clinph.2007.04.019>.
- Potter, M.C., Levy, E.L., 1969. Recognition memory for a rapid sequence of pictures. *J. Exp. Psychol.* 81, 10–15. <https://doi.org/10.1037/h0027470>.
- Potter, M.C., Staub, A., O'Connor, D.H., 2002. The time course of competition for attention: attention is initially labile. *J. Exp. Psychol. Hum. Percept. Perform.* 28, 1149–1162. <https://doi.org/10.1037/0096-1523.28.5.1149>.
- Potter, M.C., Wyble, B., Haggmann, C.E., McCourt, E.S., 2014. Detecting meaning in RSVP at 13 ms per picture. *Atten. Percept. Psychophys.* 76, 270–279. <https://doi.org/10.3758/s13414-013-0605-z>.
- Potter, M.C., Wyble, B., Pandav, R., Olejarczyk, J., 2010. Picture Detection in RSVP: Features or Identity? *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1486–1494. <https://doi.org/10.1037/a0018730>.
- Raymond, J.E., Shapiro, K.L., Arnell, K.M., 1992. Temporary suppression of visual processing in an RSVP task: an attentional blink? *J. Exp. Psychol. Hum. Percept. Perform.* 18, 849–860. <https://doi.org/10.1037/0096-1523.18.3.849>.
- RCORE, T., 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Ruiz-Martínez, F.J., Arjona, A., Gómez, C.M., 2021. Mismatch Negativity and Stimulus-Preceding Negativity in Paradigms of Increasing Auditory Complexity: A Possible Role in Predictive Coding. *Entropy* 23, 346. <https://doi.org/10.3390/e23030346>.
- Schumann, F., Steinborn, M.B., Kürten, J., Cao, L., Händel, B.F., Huestegge, L., 2022. Restoration of Attention by Rest in a Multitasking World: Theory, Methodology, and Empirical Evidence. *Front. Psychol.* 13. <https://doi.org/10.3389/fpsyg.2022.867978>.
- Shen, D., Mondor, T.A., 2008. Object file continuity and the auditory attentional blink. *Percept. Psychophys.* 70, 896–915. <https://doi.org/10.3758/pp.70.5.896>.
- Sigman, M., Dehaene, S., 2008. Brain Mechanisms of Serial and Parallel Processing during Dual-Task Performance. *J. Neurosci.* 28, 7585–7598. <https://doi.org/10.1523/JNEUROSCI.0948-08.2008>.
- Tavano, A., Widmann, A., Bendixen, A., Trujillo-Barreto, N., Schröger, E., 2014. Temporal regularity facilitates higher-order sensory predictions in fast auditory sequences. *Eur. J. Neurosci.* 39, 308–318. <https://doi.org/10.1111/ejn.12404>.
- Tomblu, M., Jolicoeur, P., 2003. A central capacity sharing model of dual-task performance. *J. Exp. Psychol. Hum. Percept. Perform.* 29, 3–18. <https://doi.org/10.1037/0096-1523.29.1.3>.
- Tomblu, M., Jolicoeur, P., 2002. All-or-none bottleneck versus capacity sharing accounts of the psychological refractory period phenomenon. *Psychol. Res.* 66, 274–286. <https://doi.org/10.1007/s00426-002-0101-x>.
- Tomblu, M.N., Asplund, C.L., Dux, P.E., Godwin, D., Martin, J.W., Marois, R., 2011. A Unified attentional bottleneck in the human brain. *Proc. Natl. Acad. Sci. U. S. A.* 108, 13426–13431. <https://doi.org/10.1073/pnas.1103583108>.
- Tremblay, S., Vachon, F., Jones, D.M., 2005. Attentional and perceptual sources of the auditory attentional blink. *Percept. Psychophys.* 67, 195–208. <https://doi.org/10.3758/BF03206484>.
- Vachon, F., Jolicoeur, P., 2011. Impaired semantic processing during task-set switching: Evidence from the N400 in rapid serial visual presentation. *Psychophysiology* 48, 102–111. <https://doi.org/10.1111/j.1469-8986.2010.01040.x>.
- Vogel, E.K., Luck, S.J., Shapiro, K.L., 1998. Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 1656–1674. <https://doi.org/10.1037/0096-1523.24.6.1656>.
- Wacongne, C., Changeux, J.-P., Dehaene, S., 2012. A Neuronal Model of Predictive Coding Accounting for the Mismatch Negativity. *J. Neurosci.* 32, 3665–3678. <https://doi.org/10.1523/JNEUROSCI.5003-11.2012>.
- Wacongne, C., Labyt, E., van Wassenhove, V., Bekinschtein, T., Naccache, L., Dehaene, S., 2011. Evidence for a hierarchy of predictions and prediction errors in human cortex. *Proc. Natl. Acad. Sci.* 108, 20754–20759. <https://doi.org/10.1073/pnas.1117807108>.
- Walsh, M.M., Anderson, J.R., 2012. Learning from experience: Event-related potential correlates of reward processing, neural adaptation, and behavioral choice. *Neurosci. Biobehav. Rev.* 36, 1870–1884. <https://doi.org/10.1016/j.neubiorev.2012.05.008>.
- Welford, A.T., 1952. The Psychological refractory period and the timing of high-speed performance - a review and a theory - ProQuest. *Br. J. Psychol.* 43, 2.

Wickham, H., 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer.

Zinchenko, A., Conci, M., Müller, H.J., Geyer, T., 2018. Predictive visual search: Role of environmental regularities in the learning of context cues. *Atten. Percept. Psychophys.* 80, 1096–1109. <https://doi.org/10.3758/s13414-018-1500-4>.

Zivony, A., Lamy, D., 2022. What processes are disrupted during the attentional blink? An integrative review of event-related potential research. *Psychon. Bull. Rev.* 29, 394–414. <https://doi.org/10.3758/s13423-021-01973-2>.