How the Brain Automatically Encodes Global Predictability: Temporal Generalization Evidence for Stable Representations

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Abstract

The brain can automatically track global information, yet the underlying mechanisms remain under debate. Although global processing, particularly of high-level structural regularities, is commonly associated with late components such as the N400, its temporal dynamics are not well understood. In this study, we employed a hierarchical roving oddball paradigm to manipulate global predictability while controlling for physical features and overall stimulus probability. EEG signals were collected while participants were passively presented with auditory inputs. ERP analysis revealed canonical MMN and P300 components. To investigate the temporal evolution of global encoding, we trained a time-resolved linear discriminant analysis to decode global predictability across time points. The resulting temporal generalization matrix showed significant cross-temporal decoding from 50 to 500 ms post-stimulus, indicating a temporally stable neural representation of global predictability. These findings suggest that the brain encodes global regularities in a sustained and temporally generalized manner, even in the absence of attention.

Keywords: Global encoding; Mismatch Negativity; Linear Discriminant Analysis; Temporal Generalization

Introduction

Auditory information unfolds over time, with local details progressively integrated into global structures. Correspondingly, the auditory system exhibits remarkable perceptual intelligence, particularly its ability to automatically track and integrate global regularities (Näätänen et al., 2010; Näätänen et al., 2001). Despite extensive research, the neural mechanisms underlying global encoding remain a topic of debate. Classical local-global paradigms implicate components such as mismatch negativity (MMN) (Recasens et al., 2014) and N400 (Liaukovich et al., 2022) in global processing, while findings based on temporal averaging suggest that early responses like N1 may also reflect integration of information over longer timescales (~5 s) (Regev et al., 2021). However, the temporal evolution of global encoding remains poorly understood.

To address this, we employed a hierarchical roving oddball paradigm and recorded EEG while participants passively listened to auditory sequences. We first identified classical ERP components, including MMN and P300. Next, we trained a linear discriminant analysis (LDA) classifier to decode global predictability and applied temporal generalization analysis to track the stability of global representations over time. This approach allowed us to characterize the dynamic trajectory of global encoding in the absence of attention.

Method

Participants (N=27) took part in the experiment, who were instructed to focus on watching a movie while ignoring the auditory stimuli presented. The hierarchical roving oddball paradigm consists of two levels. The local level involved auditory stimuli with repetitions ranging from 2 to 8, forming a stimulus cycle. Two pure-tone stimuli, 500 Hz (denoted as A) and 1000 Hz (denoted as B), alternate in varying repetition counts. The global level manipulated the repetition counts within each cycle into either ordered increasing sequences (predictable, e.g., 2:8) or random sequences (unpredictable, with random repetition counts) (see Fig. 1). This design ensures equal overall probabilities for A and B stimuli. Stimulus delivery was controlled using Psychtoolbox 3.0.19 (Kleiner et al., 2007).

EEG signals were recorded using a 64-channel Biosemi ActiveTwo system (Biosemi B.V., Amsterdam). All steps concerning preprocessing were conducted using MATLAB (version 2019a; MathWorks). The signals were re-referenced, band-pass filtered, downsampled, epoched, and baseline corrected. Artifacts were identified and removed using Independent Component Analysis (ICA) in EEGLAB. Additionally, any epochs containing artifacts exceeding ±100 μV were excluded.

We began by computing ERP difference waves, followed by extracting mean amplitudes within ±20 ms around the MMN and P300 peaks. These values were entered into regression analyses with global predictability as a predictor. Next, LDA classifiers were trained at each time point to decode global regularities. Temporal generalization analysis was applied to the global classifier, yielding a temporal generalization matrix of decoding accuracy.

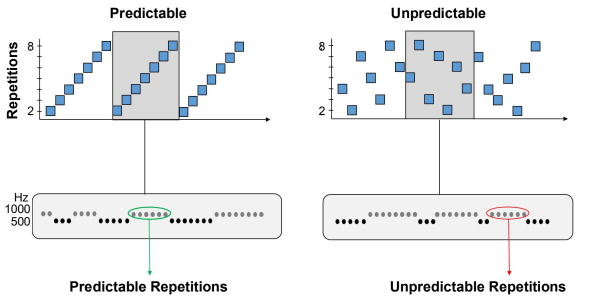

Figure 1. Schematic illustration of the hierarchical roving oddball paradigm.

Results

ERP

ERP responses at each stimulus position revealed that deviant stimuli (Position 1) elicited significant MMN and P300 components under both global conditions, as indicated by the topographical maps. However, regression analysis controlling for trial count consistency showed that neither MMN nor P300 amplitudes reliably indexed the global effect. These findings suggest that traditional ERP measures may lack sensitivity to capture global predictability effects.

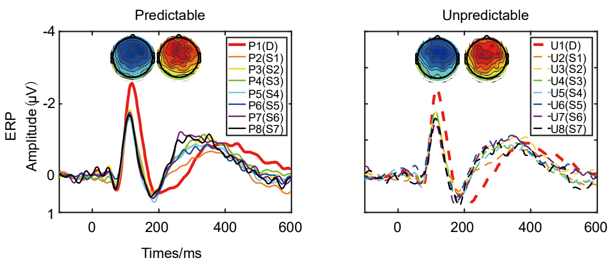

Figure 2. ERP waveforms and topographies of MMN and P300. Notably, the deviant stimulus at Position 1 evoked a distinct waveform compared to the repeated standard stimuli. Subtracting standard from deviant responses yielded classical MMN and P300 components, as illustrated in the topographical maps.

LDA decoding

The LDA-based global classifier revealed a prominent decoding peak around the classical MMN time window (~110 ms). Temporal generalization analysis further showed significant cross-temporal generalization between 50 and 500 ms post-stimulus, indicating the presence of a sustained and stable neural representation of global predictability.

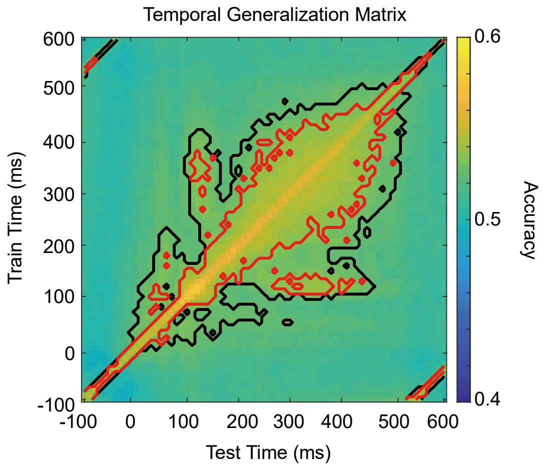

Figure 3. Temporal generalization decoding matrix. Contour lines indicate time regions where decoding accuracy significantly exceeded chance, with black and red lines marking FDR-corrected thresholds of 0.05 and 0.01, respectively.

Discussion

Taken together, our findings reveal a stable neural representation of global predictability from 50 to 500 ms post-stimulus, reconciling previous inconsistencies in the literature. The peak decoding accuracy coincided with the MMN window, providing cross-method validation of our results. By controlling physical properties and stimulus probabilities, our paradigm isolates global structural predictability as the primary driver of the observed neural effects. This demonstrates the brain's ability to track higher-order regularities over extended timescales (up to 20 seconds), even during passive listening.

Acknowledgments

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