High-caloric food induces repetition enhancement of broadband brain rhythms

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GitHub repository: https://github.com/DonEnricoEsteve/DSNS-2025.git

Abstract

Repetition enhancement (RE) is a context-dependent increase in cortical activity, occasionally elicited by repeated stimulus presentations. RE is often studied through time- and phase-locked (evoked) responses, but non-phase-locked (induced) responses may also exhibit RE, especially with salient stimuli. Sensor-level time-frequency analyses were conducted on induced MEG activity from visual presentations of high-caloric food images, presented twice at varying inter-stimulus intervals. Cluster statistics reveal significant differences that are unremarkable in global power spectral densities and spectrograms. RE occurs at three hierarchical contrast levels, each defined by three dimensions: time (M100, M200, M300 latencies), frequency (θ, α, β, γ bands), and space (sensor locations). The three-way interaction level, involving an interaction among the three factors: category, lag, and presentation (Food–Medium–2nd vs. Food–Medium–1st), reveals a significant broadband (8–50 Hz) and sustained (0.1–0.5 s) increase in cortical power, consistent with RE. This effect is induced by repeated visual presentations of high-caloric food after a medium lag, with the strongest effects over occipito-parietal sensors. This study builds on our previous efforts to elucidate food-based RE with MEG.

Introduction

Stimulus- or event-related cortical oscillatory activity recorded by M/EEG may be distinguished as evoked or induced. Both responses are time-locked but differ in phase locking: induced responses contain non-phase-locked oscillations, capturing band-specific changes in neuronal synchrony expressed as event-related (de)synchronization (ERD/ERS). This difference in signal property among many others (e.g., additivity, latency, frequency) entails diverging data manipulations to extract these two responses and, more importantly, maps onto varying aspects of cognition (David et al., 2006; Mazaheri, 2022). Repetition effects in cognition usually manifest as cortical suppression (RS), but enhancement (RE) may occur even with the same stimuli (Müller et al., 2013). For instance, identical face repetition differentially modulates induced EEG spectral power, with RS occurring in broadband gamma while RE in narrowband alpha (Engell & McCarthy, 2014). We hypothesize that other biologically and evolutionary salient stimuli, such as high-caloric food, can induce RE in MEG responses with specific time-frequency-space dynamics. In this visual paradigm, we define RE either as stronger ERD or weaker ERS, which respectively reflect increased cortical engagement and disinhibition (Strube et al., 2021; Codispoti et al., 2023). We aim to characterize sensor-level oscillatory activity from lag-modulated, repeated presentation of high-caloric food, compared with positive and neutral stimuli that respectively possess and lack perceptual salience.

Dataset Description

The dataset from the MEG-BIU Lab contains recordings from the previous 248-magnetometer system. Forty-two healthy and sated subjects viewed images from 3 categories (n=99 each): high-caloric food, positive (e.g., flowers, babies), and neutral (e.g., houses, tables). The images were evenly divided into 3 blocks, wherein each image was presented twice after a certain lag (no. intervening stimuli): short

(2), medium (16), and long (31). Oddball stimuli were included for alertness. Recordings were sampled at a rate of 1017 Hz and online band-pass filtered from 1–400 Hz. Data was preprocessed as follows: trial definition, line noise and artifact removal, low-pass filtering at 90 Hz, and ICA. The dataset contains 18 conditions, each comprising ~600 trials with a duration of 1.1 s (-0.3 to 0.8 s relative to stimulus onset).

Methods

Event-related fields (ERFs), reflecting evoked activity that is time- and phase-locked to stimulus onset, were obtained by averaging trials for each channel, condition, and subject. Assuming minimal trial-to-trial jitter in latency and amplitude, induced activity was estimated by subtracting the ERF from each trial. A multitaper Discrete Fourier Transform with a Hanning taper and zero-padding to the next power of two was applied separately to the baseline (-0.3–0 s) and post-stimulus (0–0.8 s) segments of each trial, yielding induced estimates of power spectral density (PSD) from 2 to 90 Hz in 2-Hz steps. PSDs were baseline-corrected using dB-normalization. Global PSD (averaged across channels) was computed per condition and subject and put into repeated measures ANOVA (3x3x2 factors) for each frequency band (Yoshikawa et al., 2014): theta (θ; 4–8 Hz), alpha (α; 8–13 Hz), beta (β; 13–25 Hz), and gamma (γ; 25–50 Hz). Post-hoc pairwise comparisons were performed with Bonferroni-corrected *p*-values.

Time-frequency representations (TFRs) were computed with a multitaper convolution method, with a Hanning taper and 2-s mirror padding to minimize edge artifacts and fully capture the entire trial. Spectral estimates were computed from 4 to 90 Hz in 2-Hz steps, using an adaptive time window equal to 3 cycles of each center frequency, for every 10 ms. Global condition differences were evaluated using repeated measures ANOVA for each pair of band and latency corresponding to known ERF components: M100 (100–200 ms), M200 (200–300 ms), M300 (300–500 ms). Group-level cluster-based permutation statistics assessed global condition differences with a dependent-samples T-test, using 1000 Monte Carlo randomizations for significance. Clusters are contiguous channel-frequency-time samples exceeding a two-sided threshold (α=0.05), with significance assessed using the maximum cluster statistic (α=0.025).

Results

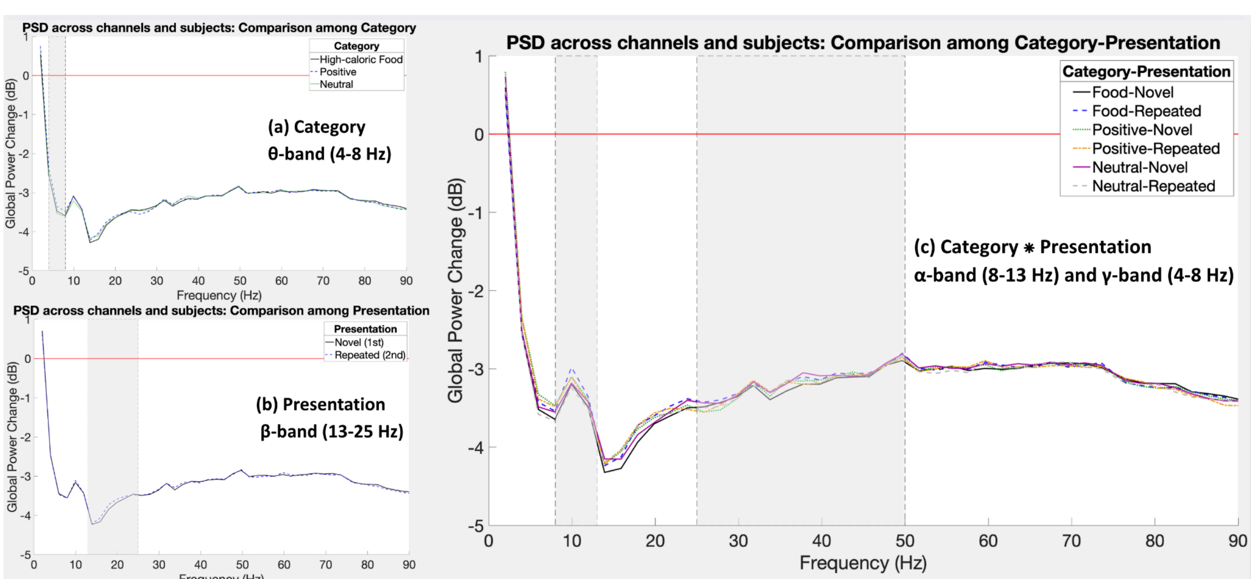


Figure 1. Global power spectral density (PSD) illustrating significant effects on induced activity: (a) main effect of Category, (b) main effect of Presentation, and (c) Category ❋ Presentation interaction. These are confined to highlighted bands. The horizontal red line indicates zero change in dB-normalized power

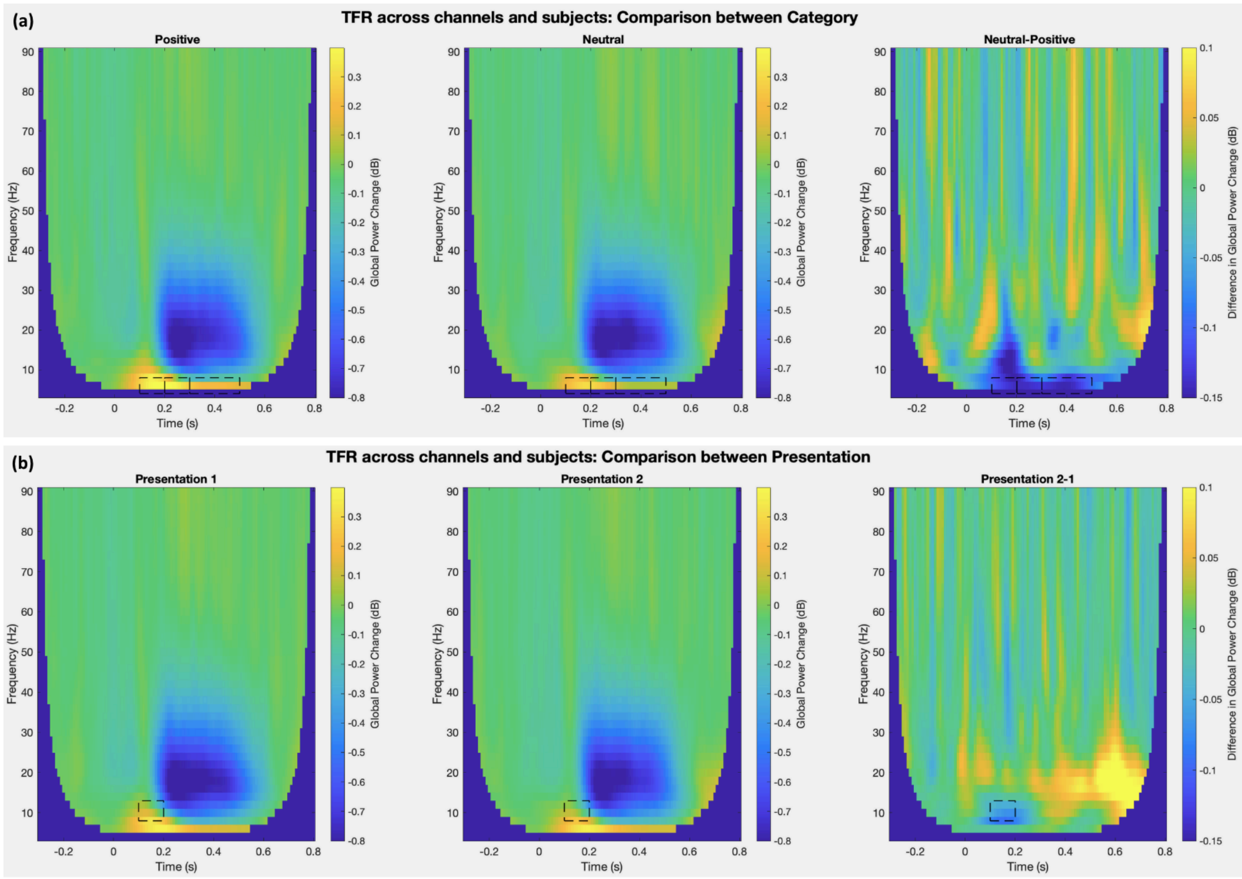


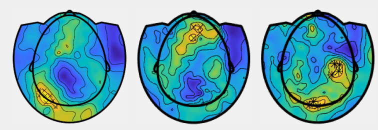
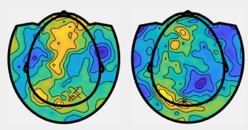
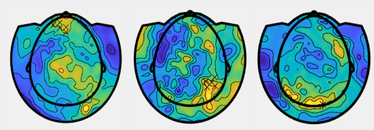
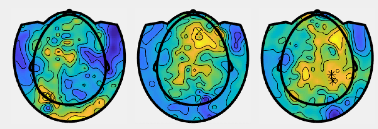
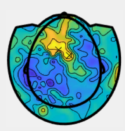
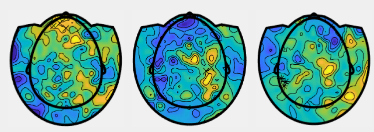
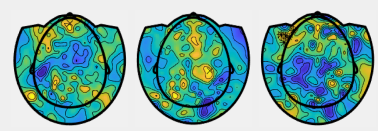
Figure 2. Global time-frequency representation (TFR) illustrating significant main effects of (a) Category and (b) Presentation confined to the overlaid bounding boxes. Color bars indicate dB-normalized power: within-condition changes for the left and middle panels, and between-condition differences for the right panels, where zero denotes no change or difference

PSD plots show that induced power decreases across frequency bands and conditions relative to the baseline, consistent with event-related desynchronization (ERD; Fig. 1). Category significantly affects θ-ERD, $F(2,82)=5.97$, $p=.004$, $\eta^2_p=.13$, with positive images inducing weaker θ-ERD than both high-caloric food ($p=.035$) and neutral ($p=.004$; Fig. 1a). Presentation significantly affects β-ERD, $F(1,41)=4.24$, $p=.044$, $\eta^2_p=.10$, with repeated presentation inducing weaker β-ERD (reduced cortical engagement) than novel, consistent with repetition suppression (RS; Fig. 1b). These factors interact (Category ✻ Presentation), significantly affecting α-ERD, $F(2,82)=3.20$, $p=.046$, $\eta^2_p=.07$, and γ-ERD, $F(2,82)=3.22$, $p=.045$, $\eta^2_p=.07$, however, post-hoc comparisons did not reveal any significant differences in both bands (Fig. 1c). Nevertheless, despite these significant main effects in the ANOVA, a simple SVM decoder with hyperparameter optimization failed to classify the data by 1st versus 2nd presentation or by category when using across-subject, across-band averaged frequency data.

TFRs temporally localize these band-specific effects, exposing transient and subtle condition differences. Category significantly affects θ-ERS across all latencies (M100: $F[2,82]=6.06$, $p=.004$, $\eta^2_p=.14$; M200: $F[2,82]=4.23$, $p=.018$, $\eta^2_p=.10$; M300: $F[2,82]=4.54$, $p=.014$, $\eta^2_p=.10$), with positive images inducing stronger θ-ERS than neutral (M100: $p=.001$; M200: $p=.010$; M300: $p=.007$; Fig. 2a) but not against high-caloric food. Presentation significantly affects α-ERS during M100 ($F[2,82]=5.02$, $p=.030$, $\eta^2_p=.11$), with repeated presentation inducing weaker α-ERS (increased cortical disinhibition) than novel, consistent with repetition enhancement (RE; Fig. 2b). Global PSD and TFR jointly suggest that repetition effects are temporally and spectrally specific, with RS and RE transiently unfolding and potentially co-occurring but across different bands. All factors interact (Category ✻ Lag ✻ Presentation), significantly affecting induced activity across all bands except γ during M300 (θ: $F[4,164]=3.61$, $p=.008$, $\eta^2_p=.08$; α:

F[4,164]=3.07, p=.018, η^2_p=.07; β: F[4,164]=2.61, p=.038, η^2_p=.06), however, post-hoc comparisons did not reveal significant differences.

Table 1. Representative topographic cluster maps for contrasts showing RE at three hierarchical levels: (left) 2nd vs. 1st, (middle) Food–2nd vs. Food–1st, and (right) Food–Medium–2nd vs. Food–Medium–1st. Cluster significance: "❋" (p<.01), "x" (p<.05). Rows and columns respectively show the a priori frequency bands and latencies. Colormap represents cluster T-values.

	M100 (0.1–0.2 s)	**M200 (0.2–0.3 s)**	**M300 (0.3–0.5 s)**
θ			
α			
β			
γ			

Cluster plots spatially localize these specific band-latency effects, explicating repetition effects by reconciling findings from PSDs and TFRs and exposing pairwise differences underlying global interactions. Repetition effects are evident in all a priori bands except the θ-band (Table 1, first row), which is instead primarily modulated by image category (Figs. 1-2). Repetition effects also emerge more reliably at later latencies. These reinforce its dependence on time-frequency dynamics. All contrasts show a positive cluster (p=.016, p=.044, p<.001), reflecting significantly higher band-latency-specific power for repeated conditions (i.e., 2nd, Food-2nd, Food–Medium–2nd) than the respective novel conditions (i.e., 1st, Food-1st, Food–Medium–1st) across varying sensors. Cluster locations for each contrast are more similar across adjacent bands and latencies than across distant ones. For instance, in the 2nd vs. 1st contrast, clusters emerge over left occipitotemporal sensors within the α- and β-bands during M300; over frontal sensors within the γ-band during M200 and M300 (Table 1). These collectively suggest that RE may engage widespread cortical regions. Furthermore, cluster locations differ among contrasts even within identical band-latency (e.g., α-band during M300), showing the modulation of RE by interacting with category (Food–2nd vs. Food–1st), and category–lag (Food-Medium-2nd vs. Food–Medium–1st).

The latter contrast uniquely demonstrates RE, as induced activity upon the second presentation of high-caloric food after a short (Food–Short–2nd) or a long (Food–Long–2nd) lag does not significantly differ from those of the respective novel conditions. The temporal progression of the Food-Medium-2nd vs. Food–Medium–1st contrast, evident in the β-band (Table 1, third row, right panels), reflects the visual nature of the stimuli: clusters emerge during M100 over occipital sensors near V1, persist through M200, and eventually shift during M300 over parietal sensors near higher-order visual areas.

Discussion

The directionality of repetition effects on induced activity is contingent on time, frequency, and space, paralleling observations in evoked activity such as visual ERP (Hsu & Lee, 2023) and auditory ERF

(Recasens et al., 2014). This reinforces the often-understated view that evoked and induced oscillations are linked, arising from shared generative neuronal mechanisms (David et al., 2006; Mazaheri, 2022). RE is prominent broadband during M300 (Table 1), which aligns with higher-order cognitive processing such as attention allocation and memory formation (Polich, 2007). Beyond the three dimensions defining RE, its unfolding can also be characterized across the three hierarchical contrast levels (Table 1). The main contrast (Presentation) captures the general phenomenon. The two-way interaction contrast (Category ❋ Presentation) shows that RE occurs for high-caloric food, whose appetitive salience and energetic value associate with prolonged attention and reduced habituation (Duraisingam et al., 2021). The three-way interaction contrast (Category ❋ Lag ❋ Presentation) shows that food-based RE occurs only with medium lag, revealing a "Goldilocks" inter-stimulus interval long enough to prevent RS driven by habituation with shorter lags, yet also short enough to prevent memory trace decay with longer lags (Xue et al., 2011). This study offers insights into food-related visual processing, which has economic, ecological, and clinical implications. Systematic variation of time-frequency decomposition parameters and source-level analyses would validate these findings and are important avenues for future research.

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