Theta EEG Dynamics of the Error-Related Negativity

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Overview

Two views of the genesis of the error-related negativity (ERN) are contrasted: the classic view that time-locked phasic bursts give rise to the ERN versus a view that the ERN is generated - at least in part - by a phase-resetting and amplitude enhancement of ongoing theta (4 -7 HZ) EEG activity. Time domain ERP analyses, time-frequency investigations of phase-locked and non-phase-locked spectral power and inter-trial phase coherence (ITPC) computed from individual EEG trials were applied to empirical data, and simulations of the classic and phase-resetting views were implemented. An increase in total power (phase- and non-phase-locked) was significantly larger than phase-locked power, indicating that the bulk of the theta event-related dynamics were not phase-locked to response. Results of the simulations revealed a good fit for data simulated according to the phase-locking with amplitude enhancement perspective, and a poor fit for data simulated according to the classic view. Error responses are thus associated with not only larger phase-locked increases in theta EEG activity, but also increases in non-phase-locked theta, all of which share a similar topography. These findings are consistent with the notion advanced by Luu et al. (2004) that the ERN emerges, at least in part, from a phase-locking of ongoing theta-band activity, in the context of a general increase in theta power following errors.

Methods

- Participants (n=21) performed Erikson Flanker task (SSHSS) with 1280 trials; Error rate = 9.7%
- Self Correction encouraged; only self-corrected error trials included along with correct trials
- A subset of trials were selected to allow for matching of correct and error trials
  - Three potentially confounding variables matched
    - Reaction time
    - Total number trials
    - Presence/absence of ocular artifact within 500 msec post-response
  - Resulted in average of 124 error trials and 119 matched correct trials per person
- EEG was recorded from 25 scalp sites; all data ocular artifact corrected using Semlitsch (1986) algorithm
- Simulations of the classic hypothesis and the phase-resetting amplitude enhancement hypothesis were constructed, constrained to mach the amplitude of individual subjects' ERPs.

Results: Time Domain Averages

Error responses were characterized by the expected ERN, maximal at Cz

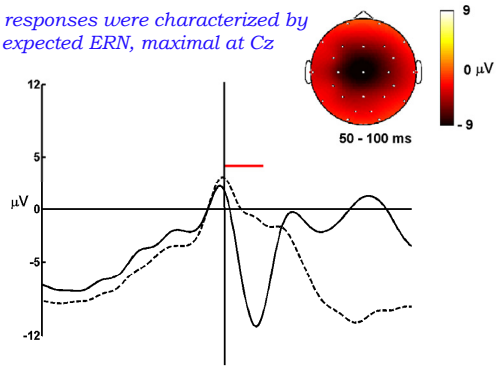

Figure 1. Grand-average wide-band (0.1 - 15 Hz) filtered waveforms for Correct and Error responses at site CZ. Solid black line = Error responses, dashed black line = Correct responses, solid red line = time intervals containing statistically significant ($p < 0.05$, two-tailed) Error vs. Correct differences. Inset shows wide-band ERN difference waveform (Error - Correct) scalp topography.

Poster handout available at: http://www.psychofizz.org

Results: Time-Frequency Analyses

Error responses were characterized by an increase in phase-locked theta power and a more pronounced increase in total theta power, as well as an increase in inter-trial phase coherence. Correct responses had significantly less increase in power and phase coherence

Details

- Raw EEG data were convolved with Morlet wavelets to yield the wavelet transform for:
  - phase-locked power – estimating the magnitude of EEG oscillatory responses that demonstrate relative phase consistency across trials (Time-frequency of ERP)
  - total power estimating both phase consistent and inconsistent portions of the EEG oscillatory signals (Average Time-frequency of individual EEG epochs)
- Inter-trial phase coherence (ITPC) is the phase of the wavelet at time t and frequency f. In its standard form ITPC indexes the phase consistency of EEG signals across trials at a given latency, with ITPC values range from 0 (indicating absence of phase-locking) and 1 (indicating perfect phase synchronization). All ITPC values were baseline-corrected over the same interval as the spectral power values, and were computed for each participant.

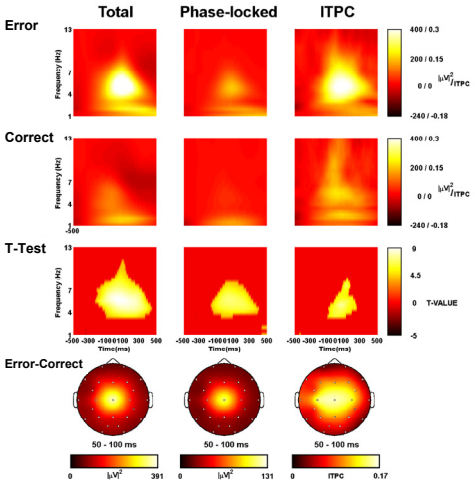

Figure 2. Empirical data time-frequency grand-average total power (left column), phase-locked power (center column) and ITPC (right column) at site CZ. Light colors indicate increases with respect to the pre-response baseline; dark colors indicate decreases. Total power is derived from analysis of single trials, and phase locked from analysis of average waveforms. T-test values were derived via non-parametric bootstrapping and permutation t-tests.

Results: Simulations

Error and correct EEG data epochs were simulated for each individual participant by adding a basic theta range ERN waveform onto uncorrelated background noise. Simulation of the phase-resetting with amplitude enhancement hypothesis created a good fit to the empirical data in terms of the average waveform, and also total power, phase-locked power, and inter-trial phase coherence. Simulation of the classic hypothesis had a comparatively poor fit, as depicted in the plots of the permutation t-tests comparing empirical to simulated data.

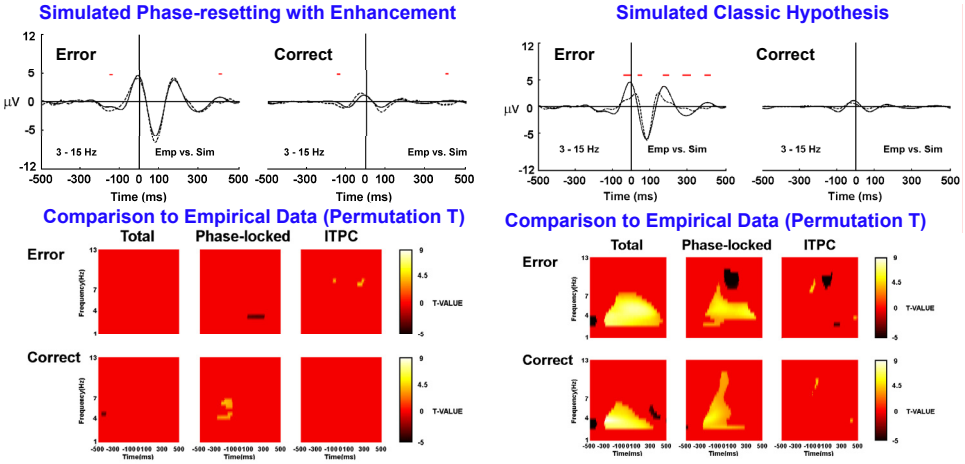

Figure 3. Top Panels: Grand-average simulated and empirical waveforms for Correct and Error responses. Solid black line = empirical data, dashed black line = simulated data, solid red line = time intervals containing statistically significant ($p < 0.05$, two-tailed) Empirical Vs. Simulation differences. Lower Panels: results of permutation t-tests comparing Empirical to Simulated data in terms of Total Power, Phase-locked Power, and Inter-trial Phase Coherence.

Conclusion

Error responses are associated with not only phase-locked increases in theta EEG activity, but also increases in non-phase-locked theta that share a similar topography. Simulations provide a good fit for the phase-locking with amplitude enhancement perspective, and a poor fit for the classic view. These findings suggest that the ERN emerges, at least in part, from a phase-locking of ongoing theta-band activity, in the context of a general increase in theta power following errors.