Prelude to and Resolution of an Error: EEG Synchrony Reveals the Ongoing Dynamics of Performance Monitoring

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Abstract

❖ **The error-related negativity (ERN) is an electrophysiological signature of response errors thought to be generated by phase resetting of theta (4-8 Hz) in the medial frontal cortex, especially anterior cingulate cortex (ACC).**

❖ **It is thought that the ACC works in conjunction with lateral prefrontal cortex (LPFC) to maintain cognitive control.**

❖ **To date, the neural mechanism by which this ACC-LPFC interaction occurs remains unknown.**

❖ **We hypothesized that transient synchronous oscillations between ACC and LPFC, particularly in the theta range, reflect the mechanism by which these structures interact.**

General Methods

- 14 introductory psychology students (6 female; age M=18.86, ±SD=.95)
- Erikson Flankers Task: 400 trials total, with 200 congruent (i.e.: MMMMM) and 200 incongruent (i.e.: MMNMM) trials.
- 62 scalp channels recorded on a Synamps[2], 500X amplification, 500 Hz sampling rate, band passed .01-100 Hz, impedances < 10 KΩ.
- Reaction time matching algorithm selected a correct trial with the closest RT to each error response, for each participant. Minimum number of errors was 30. Participants made an average of 52.2 (±SD=20.1) errors, with similar reaction times for error (M=427.0, ±SD=71.0) and reaction time matched correct trials (M=438.7, ±SD=63.1)
- EEG was converted to Current Source Density (CSD) per the methods of Kayser & Tenke (2006). CSD acts as a reference-free low-pass spatial filter, highlighting local electrical activities at the expense of diminishing the representation of distal activities (volume conduction).
- All CSD-ERPs were created at the FCz electrode by filtering (1-15Hz), baseline correcting (-100 to 0 ms), and cutting the length (-300 to +500 ms) of each raw CSD epoch before averaging. CSD-ERPs were measured as the size of the difference between the largest trough (between 0-120 ms) and the preceding peak, with a larger CSD-ERP component (i.e. a more negative ERN) quantified as a larger positive value.

Time / Frequency Methods

- The CSD-EEG time series in each epoch was convolved with a set of complex Morlet wavelets, defined as a Gaussian-windowed complex sine wave:

$$e^{-i2\pi tf}\, e^{-t^2/(2*\sigma^2)}$$

- Power (the magnitude of the analytic signal) was defined as:

$$Z[t]\ (\text{power time series: } p(t) = \text{real}[z(t)]^2 + \text{imag}[z(t)]^2)$$

- Power was normalized by conversion to a decibel (dB) scale:

$$10*\log10[\text{power}(t)/\text{power}(\text{baseline})]$$

- Phase (the phase angle) was defined as:

$$\arctan(\text{imag}[z(p(t))]/\text{real}[z(p(t))])$$

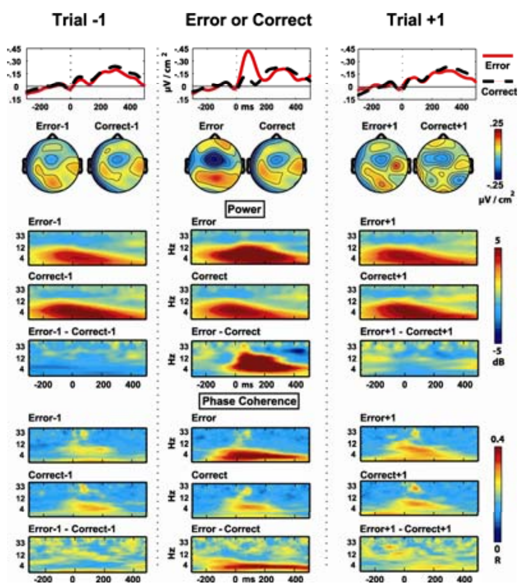
- Inter-*Trial* Phase Coherence (ITPC) measures the consistency of phase values for a given frequency band at each point in time over trials, in one particular electrode. ITPC was defined as:

$$ITPC = \left|\frac{1}{n} * \sum_{x=1}^{n} e^{i\phi_{xt}}\right|$$

- Inter-*Channel* Phase Coherence (ICPC) measures the extent to which oscillation phases are similar across different electrodes over time/frequency. ICPC was defined as:

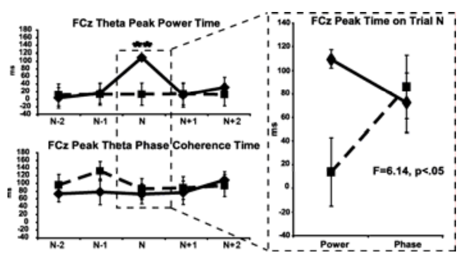
$$ICPC = \left|\frac{1}{n} * \sum_{t=1}^{n} e^{i[\phi_{jt} - \phi_{kt}]}\right|$$

- All Power, ITPC and ICPC measures were quantified as the average value (and time of peak) of the theta band (4-8 Hz) in a -100 to 300 ms window around the response.

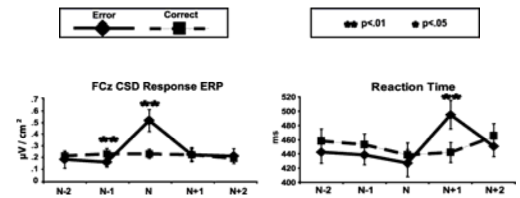


Response locked CSD grand averages for N-1 (left), N (center) and N+1 (right) trials. Three different measures of event-related EEG are shown: 1) CSD-ERPs and topographic maps, 2) Power in dB, and 3) Inter-trial phase coherence. Note the increase of power and phase coherence following an error, especially around 4-12 Hz and 4 Hz, respectively.

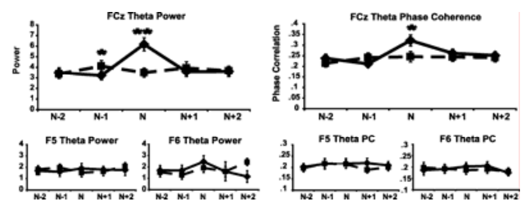
Power / Latency Dissociation



Differences in peak latency for power and phase coherence at the FCz site. This accuracy-related difference shows that phase coherence latency is constant but peak power occurs much later following an error.



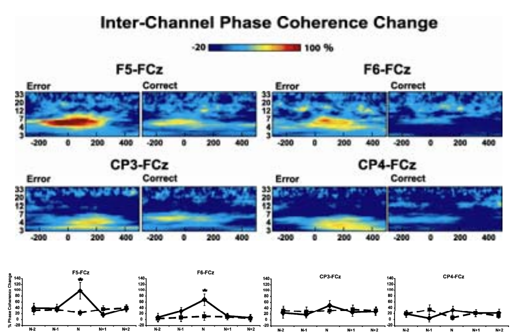
Time courses of CSD activities (Mean ± SE). CSD-ERPs show decreased activity preceding an error, and increased activity immediately following an error. The reaction time plot shows post-error slowing.



Time courses of CSD activities (Mean ± SE). Averaged FCz (mPFC) power demonstrates similar dynamics as the CSD-ERP, but F5 and F6 (lPFC) sites show no accuracy-related modulation. Averaged FCz ICPC increases following errors, but F5 and F6 sites show no accuracy-related modulation.

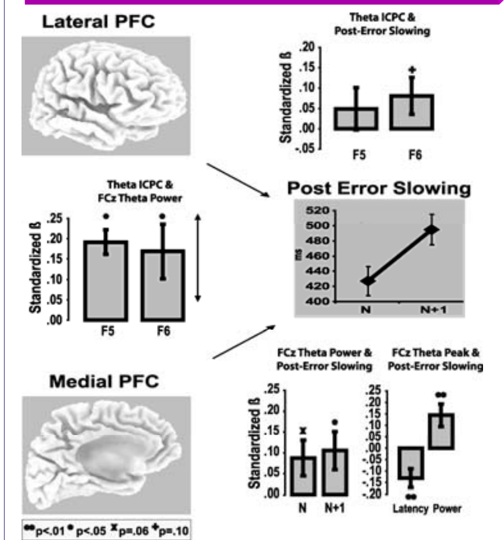
Note that ordinate scaling on FCz plots are 200% of the F5 and F6 ordinate.

mPFC-lPFC Phase Coherence



Grand averaged inter-channel phase coherence (percent change from baseline). ICPC is increased following errors, with robust increases in the theta band at frontal sites.

A Conflict – Control Network



Single trial analyses of the proposed conflict-control network. The degree of post-error slowing is robustly predicted by increased theta power and a shorter latency to peak power at FCz. Although FCz power is predicted by theta ICPC with lPFC sites (F5 and F6), the degree of this ICPC only predicts post-error slowing at the level of a statistical trend.

Conclusion

❖ **Long-range oscillatory synchrony in the theta band may be one mechanism by which a conflict-control network is instantiated in the prefrontal cortex.**

❖ **This oscillatory synchrony may capitalize on an inherent background of medial frontal theta band oscillatory perturbation and power increase during demanding manual responses.**

❖ **Errors may induce altered oscillatory dynamics in this system, which in turn support enhanced computation and inter-regional communication.**

❖ **The findings of this investigation suggest that the dynamic oscillatory interplay between medial and lateral frontal regions underlies our ability to detect errors and adjust behavior accordingly.**

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Handouts available: www.psychofizz.org **Contact:** jimcav@email.arizona.edu