MEDIAL PFC THETA POWER SCALES WITH DEGREE OF NEGATIVE FEEDBACK PREDICTION ERROR

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Abstract

✦ Investigations into action monitoring have consistently detailed a fronto-central voltage deflection following negatively valenced feedback, often termed the Feedback Related Negativity (FRN).

✦ The FRN has been proposed to reflect a neural response to **negative prediction errors**, yet the single trial relationship between neural activity and the quanta of expectation violation remains untested.

✦ Here we fit performance data on a learning task to an abstract computational model (Q-learning) for calculation of single-trial reward prediction errors.

✦ Although ERP methods are not well suited to single trial analyses, the FRN has been associated with theta band oscillatory perturbations in the medial prefrontal cortex.

✦ Single-trial theta oscillatory activities following feedback were investigated within the context of expectation (prediction error) and adaptation (subsequent reaction time change)

✦ Results indicate that interactive medial and lateral frontal theta activities reflect the degree of negative and positive reward prediction error in the service of behavioral adaptation.

Methods

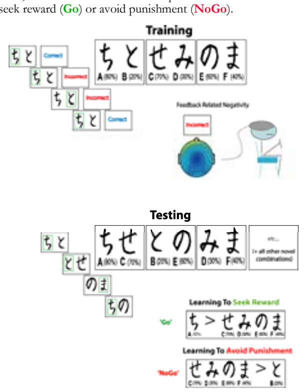
Participants

❖ Participants (N=50, 26 female) were an average of 19 years old (SD= 1.35).

Reinforcement Learning Task

❖ A probabilistic reinforcement learning task was used (Frank et al, 2004). During the **training** phase, three pairs of symbols are learned solely by the feedback provided after each forced choice. The feedback is probabilistic and will reinforce the 'correct' choice only 80%, 70% or 60% of the time, depending on the stimulus pair.

❖ Learning is assessed in a subsequent **test** phase, where all possible stimulus pairs are presented and participants must choose the "best one", without feedback. This **test** phase revels the bias to learn to seek reward (**Go**) or avoid punishment (**NoGo**).



Q-Learning

❖ The expected value (Q) of any stimulus (i) at time (t) was computed after each reinforcer (R=1 for Correct, R=0 for Incorrect), with difference learning rates (α) for Gain and Loss:

$$Q_i(t+1) = Q_i(t) + \alpha G\,[R(t) - Q_i(t)]_+ + \alpha L\,[R(t) - Q_i(t)]_-$$

❖ Q values were entered into a softmax logistic function to produce probabilities (P) of responses for each trial choice (i) over all choices (j), softened by exploration (β):

$$Pi(t) = \exp(Q_i(t) / \beta) / \Sigma j \exp(Q_j(t) / \beta)$$

❖ These probabilities (P) are then used to compute the log likelihood estimate (LLE) that the subject completed that complete sequence of responses:

$$LLE = \sum_t \ln(P_i(t))$$

❖ Prediction errors (PE) for each subject were then computed on a trial-by-trial basis from the estimated Q value of the chosen stimulus at that time:

$$PE = R(t) - Q_i(t)$$

EEG

❖ 62 scalp channels recorded on a Synamps², 500X amplification, 500 Hz sampling rate, band passed .01-100 Hz, referenced online to a near-vertex site, referenced offline to CSD.

❖ 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:

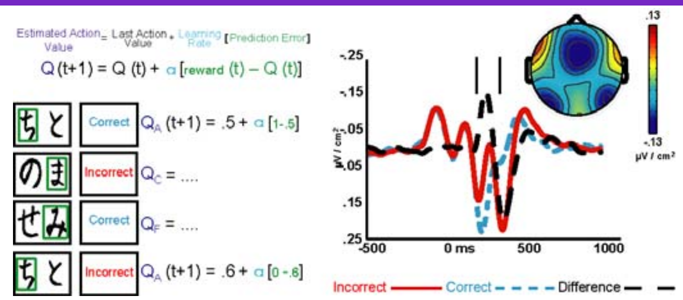
$$e^{-i2\pi f}\, e^{-t^2/(2*\sigma^2)}$$

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

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

❖ All power and phase measures were quantified as the average value in the theta band (4-8 Hz) in a 200 – 500 ms window following feedback.

Q Learning & the FRN

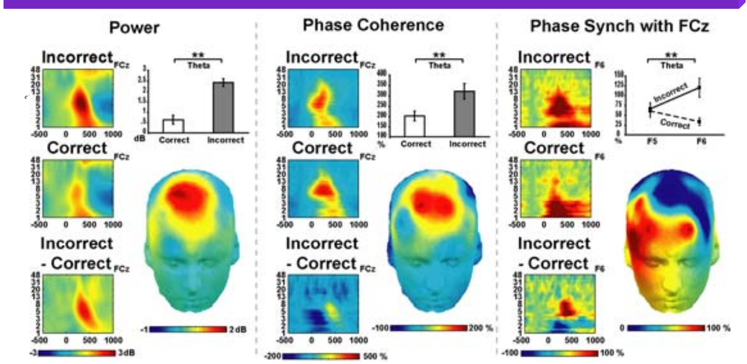


✦ Following positive feedback, action values will increase, updating the likelihood of choosing the same stimulus in the future.

✦ Prediction errors occur in relation to the extant action value. If a negative prediction error occurs in relation to a large action value, the PE is even worse than expected.

✦ Negative prediction errors have been proposed to be reflected by the Feedback Related Negativity (FRN) component of the ERP.

mPFC Theta to Feedback

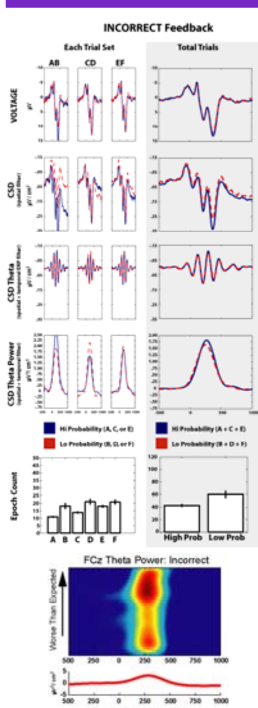


✦ Grand average time- frequency plots show CSD power, phase coherence increases from baseline, and phase synchrony increases from baseline.

✦ A strong theta band increase can be seen following incorrect feedback ~300-500 ms; these effects are significantly different between conditions (as shown in the bar and line charts).

✦ Topographic plots show difference wave distributions (averaged over 300-500 ms) for the theta band.

FRN & mPFC Theta



✦ Feedback-locked grand average signals at FCz for correct and incorrect feedback:
- ✦ Voltage (.5-20 Hz)
- ✦ CSD (.5-20 Hz)
- ✦ CSD theta (4-8 Hz)
- ✦ CSD theta power (4-8 Hz)

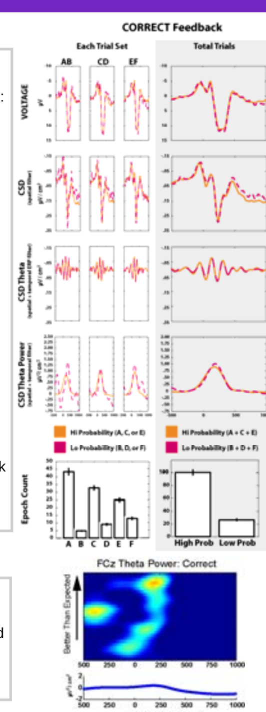
✦ Within each accuracy plot, the left side details feedback traces that are overlapped within each training pair. On the right side of each (grey border), all trials are averaged together.

✦ There is no evidence for component overlap due to change in condition-wide expectancy or due to volume conduction in theta band filtered CSD-EEG.

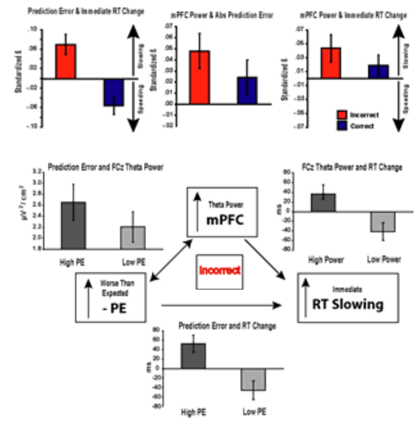
✦ Theta power is larger to incorrect feedback, but the lack of condition-wide expectancy differences suggest the need for single-trial analyses.

✦ Grand averaged ERPplots

✦ Theta CSD power from the FCz electrode for incorrect and correct conditions, smoothed and sorted by degree of prediction error.



Worse Than Expected



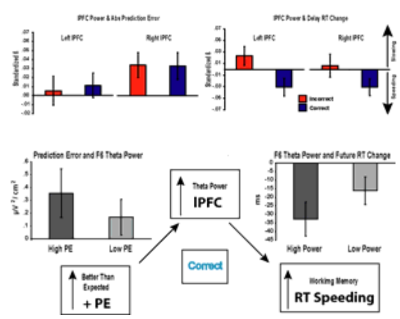
✦ The magnitude of prediction error is related to immediate reaction time slowing following incorrect feedback and speeding following correct feedback.

✦ Following incorrect feedback, the magnitude of negative prediction error and the amplitude of medial PFC theta were directly related to each other. Both of these measures predicted the degree of immediate reaction time slowing in single trial analyses (median split for display).

✦ -PE does not significantly predict reaction time slowing when shared variance with mPFC theta is accounted for.

✦ **Medial PFC theta power may be a reflection of a system that uses negative prediction errors to immediately adapt behavior.**

Better Than Expected



✦ Following correct feedback, the magnitude of positive prediction error was directly related to the amplitude of lateral PFC theta power.

✦ Lateral PFC theta power predicted reaction time speeding for the same trial type the next time it was encountered (after a delay).

✦ **Lateral PFC theta power may be a reflection of a system that updates working memory for stimulus value in the service of future behavioral adaptation.**

Summary

✦ Medio-frontal theta band activities, which presumably underlie the FRN component, are reflective of the degree of negative prediction error and subsequent behavioral adaptation.

✦ Multiple neural systems may be involved in the computation of different types of prediction error for different behavioral adaptations.

✦ Theta band oscillations may be reflective of prediction error calculations:
- **✦ In medial PFC for immediate behavioral adaptation following punishment**
- **✦ In lateral PFC for delayed behavioral adaptation following reward**

Handouts available: www.psychofizz.org Contact: jim.f.cav@gmail.com