Rhythmic interactions between early visual areas and prefrontal cortex predict bistable perception

Yanni Zhang (yannizhangx.x@gmail.com), Biao Han (raintwoto@gmail.com), Qi Chen (qi.chen27@gmail.com), Lu Shen (lu.shen2013@gmail.com)
South China Normal University, Guangzhou

Abstract

Visual perception integrates external stimuli with the brain's intrinsic dynamics, particularly under ambiguity. Predictive processing posits that hierarchical oscillations act as dynamic priors to resolve uncertainty, yet how cross-regional signals are temporally coordinated remains unknown. To address it, we combined the bistable Ternus paradigm—eliciting element motion (EM) or group motion (GM), depending on the observer's internal state —with intracranial EEG (iEEG) in six patients to explore prefrontal-visual oscillatory dynamics. We found that prestimulus alpha phase in early visual areas (V1-V3) and theta phase in prefrontal cortex (PFC) predicted perceptual outcomes. Directed connectivity analyses revealed stronger low-frequency (2-8 Hz) coupling from PFC to visual regions during EM percept, indicating top-down predictive signaling. These findings suggest that coordinated pre-activated dynamics between early visual areas and the PFC play a critical role in shaping perceptual outcomes, offering insights into how intrinsic neural processes influence conscious visual perception.

Keywords: alpha oscillations; early visual areas; prefrontal cortex; bistable perception

Introduction

Visual perception is an active, inferential process where the brain resolves sensory ambiguity via predictive processing (Clark, 2013; Friston, 2010). Neural oscillations in the theta and alpha bands contribute to this process, with prestimulus activity modulating behavioral performance (Busch et al., 2009; Cecere et al., 2015; Ronconi & Melcher, 2017; Shen et al., 2019).

The PFC plays a key role in top-down modulation of visual cortex activity during tasks involving uncertainty (Bellet et al., 2022; Fyall et al., 2017) and increased difficulty (Kar & DiCarlo, 2021). Functional interactions between the PFC and visual cortex have been shown to occur in conditions of greater task difficulty (Jiang & Kanwisher, 2003). The thalamus, especially the pulvinar, modulates visual cortex activity, aligning with sensory demands (Saalmann et al., 2012). These findings suggest that higher-order cortical areas, like the PFC, modulate intrinsic activity in visual areas to influence perception under ambiguous conditions.

We analyzed iEEG data from six patients performing a Ternus task and found that prestimulus early-visual (V1-V3) alpha phase and PFC theta phase predicted perceptual outcomes. Prestimulus directed connectivity from PFC to visual areas was stronger for element motion (EM) than group motion (GM), highlighting the role of low-frequency interactions in shaping perception.

Methods

Data were collected from 6 patients (two female; mean ± SD, 23.33 ± 6.19 years) with drug-resistant focal epilepsy undergoing neurosurgical treatment. Visual stimuli consisted of two frames of black disks shown for 30 ms each, with varying interframe intervals (IFIs). Participants were asked to perform a two-alternative forced-choice task to discriminate apparent motion.

We evaluated prestimulus low-frequency phase differences between perceptual outcomes using the Phase Opposition Sum (POS). Additionally, phase-based connectivity was assessed using the weighted Phase Lag Index (wPLI-debiased) and the Phase Slope Index (PSI) to investigate phase coupling between the prefrontal cortex (PFC) and early visual areas.

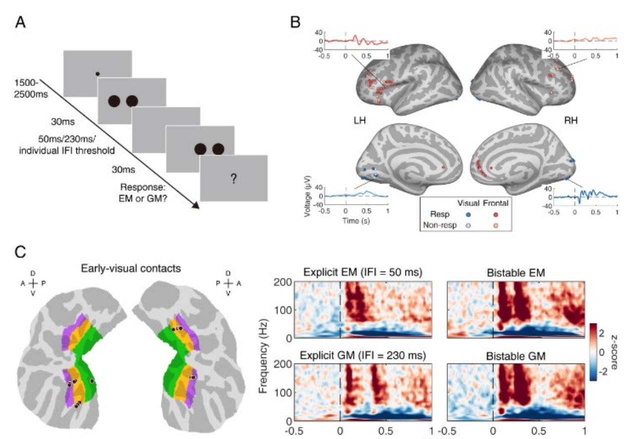

Figure 1. (A) Experimental paradigm. (B) Anatomical locations of four groups of contacts. (C) Left panel: locations of ERP-responsive early-visual contacts, visualized on a flattened common occipital patch. Right

panel: mean time-frequency power representations of early-visual contacts across patients under different conditions.

Results

Prestimulus alpha phase in the early visual areas predicts perceptual outcomes

We examined whether prestimulus low-frequency phase in early visual areas modulates perceptual outcomes in bistable vision. Using phase opposition sum (POS), we identified significant phase differences between element motion (EM) and group motion (GM) trials from -420 ms to stimulus onset (cluster-corrected p = 5.00×10^{-3}; Fig. 2A). Trials were binned by alpha phase (7 Hz, -200 ms) at the peak modulation time-frequency point. A one-way ANOVA revealed that prestimulus alpha phase significantly predicted GM proportion ($F(5,18) = 3.60$, $p = 0.02$), with ~12% variance in perceptual outcomes explained by phase binning (Fig. 2B).

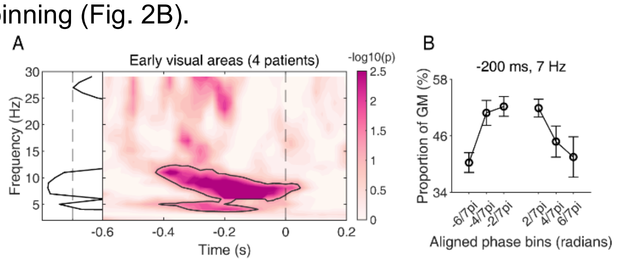

Figure 2. (A) Prestimulus early-visual alpha phase difference between EM and GM. (B) Relationship between pre-stimulus alpha phase and the proportion of GM (at 7 Hz; -200 ms) at the group level.

Prestimulus theta phase in the prefrontal cortex predicts perceptual outcome

Shifting focus to PFC, we applied phase opposition sum (POS) analysis and identified prestimulus theta-phase differences (3–5 Hz, -600 to -120 ms) predictive of perceptual outcomes ($p = 0.02$, cluster-corrected; Fig. 3A). Binning trials by theta phase (peak: -360 ms, 4 Hz) revealed significant modulation of group motion (GM) proportion ($F(5,18) = 7.55$, $p = 6.00\times10^{-4}$), with theta phase explaining ~14% variance in perception.

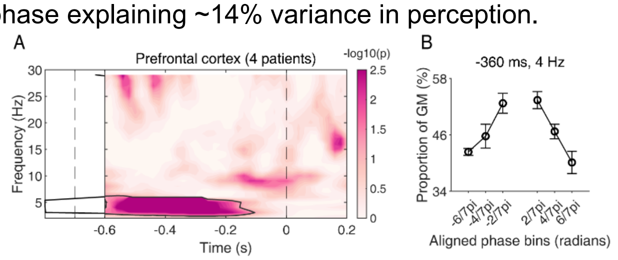

Figure 3. (A) Prestimulus prefrontal theta phase difference between EM and GM. (B) Relationship between pre-stimulus alpha phase and the proportion of GM (at 4 Hz; -360 ms) at the group level.

Prestimulus prefrontal-early visual connectivity predicts perceptual outcome

We then asked whether these two regions connected on a trial-by-trial basis. To this end, we computed the debiased weighted phase lag index (wPLI-debiased) between early-visual and prefrontal contact pairs of two patients. The resulting time-frequency representation of wPLI-debiased across all trials showed significant prestimulus prefrontal-early visual phase synchronization in the theta band for both patients (Fig. 4A). We further found that this directed connectivity was predictive of perceptual outcomes. The prefrontal cortex appeared to lead theta-band activity in the early visual areas to a significantly greater degree than chance under EM condition (Fig. 4B). Conversely, under GM condition, the connectivity patterns did not exhibit any clear directionality.

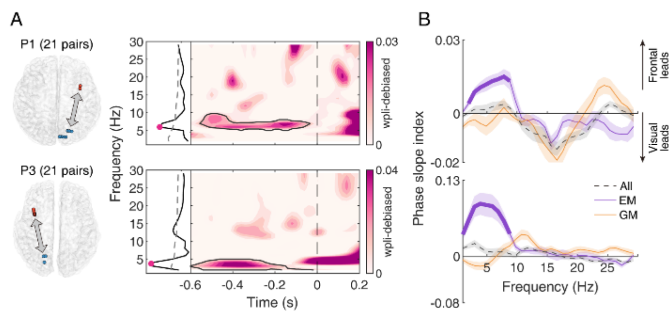

Figure 4. (A) Left panels: contact locations. Right panels: Time-frequency representations of wPLI-debiased between these two regions. (B) Patient-specific frequency spectrum for prestimulus directed connectivity between these two regions.

Discussion

Using intracranial EEG, we found that prestimulus oscillatory dynamics in the prefrontal cortex (PFC) and early visual areas (V1-V3) predict perceptual outcomes during the bistable Ternus task. Notably, stronger low-frequency coupling from the PFC to visual areas preceded element motion (EM) percepts, suggesting top-down predictive signaling. These findings indicate that theta-band connectivity between PFC and early visual areas to stabilize perception under ambiguity, highlighting the role of hierarchical oscillatory interactions in resolving sensory uncertainty.

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