How Theta Rhythms May Coordinate Attention Streams in FEF and IFJ: A Clock-and-Data Hypothesis

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Abstract

While the classic "what" vs. "where" split in visual attention is well-supported anatomically, less is known about how these streams avoid temporal interference. Building on the Communication Through Coherence (CTC) framework, this report reviews evidence how the Frontal Eye Field (FEF) and Inferior Frontal Junction (IFJ) control dorsal and ventral visual pathways via distinct oscillatory frequencies. I propose a "Clock-and-Data" hypothesis, in which a theta-rhythmic pacemaker organizes the timing of beta- and delta-band routing in FEF and IFJ to keep spatial and object-based attention streams temporally segregated.

1 Introduction

Selective attentional routes have long been distinguished into "what" and "where" pathways. But while this anatomical split is well-supported, one key question remains: how do these parallel streams avoid interfering with each other, especially when they target overlapping regions like V4 or IPL?

One possible answer lies not in where signals go, but in when they go. Neural communication is not just sequential firing, but rhythmic. Classic models suggest that top-down attention is mediated by low-frequency oscillations (alpha, beta), while bottom-up signals are carried by faster gamma activity (Buschman and Miller, 2007). But how does the brain prevent multiple parallel top-down routes from interfering?

Fries' Communication-Through-Coherence (CTC) framework adds a possible apporach to solving the temporal solution: According to this model, effective communication between two brain areas depends on whether their oscillations align in phase, opening up "windows of excitability" (Fries, 2015). Anatomical connections alone are not enough. Without phase alignment, signals get ignored.

Recent evidence supports the idea that the Frontal Eye Field (FEF) and Inferior Frontal Junction (IFJ) coordinate different visual pathways using different frequency bands. FEF couples with dorsal stream areas (e.g., SPL) through beta and gamma rhythms, supporting spatial attention (Veniero et al., 2021). IFJ, by contrast, connects to ventral stream areas via delta and gamma, modulating object-based attention (Baldauf and Desimone, 2014). This raises a new question: What mechanisms enforce this separation in time?

While FEF and IFJ operate mostly in distinct frequency bands, this alone may not guarantee interference-free transmission. Temporal overlap could still occur unless their outputs are coordinated relative to a common timing structure. I hypothesize that a shared theta rhythm may actively enforce this separation by assigning distinct temporal slots to each stream possibly through a precession-like mechanism similar to what has been observed in the hippocampus (Jensen and Colgin, 2007).

2 Theoretical Background

2.1 Communication-Through-Coherence

The CTC framework explains how temporal phase alignment between brain regions gates effective information flow. According to Fries (Fries, 2015), communication is only successful when the sender's output arrives during the receiver's high-excitability phase, forming a temporary "window" for input. Even anatomically connected regions cannot communicate functionally without this phase synchrony. This theory has become central to understanding how oscillatory dynamics contribute to selective information routing in the brain.

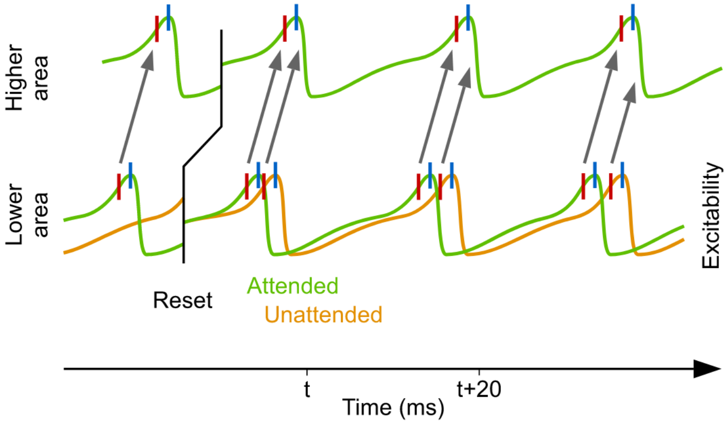


Figure 1: Theta-rhythmic phase resets align gamma rhythms across stimuli. After such a reset, gamma-band activity represents attended (green) and unattended (orange) stimuli that start in the same phase. The attended representation oscillates at a higher frequency, causing its input to arrive earlier in higher cortical areas. This temporal lead suppresses competing inputs (Fries, 2015)

2.2 Theta Oscillation Resets

CTC predicts that lower areas must sometimes be reset by higher-order regions to ensure phase alignment. Initial evidence by Bosman et al. (2012) demonstrated, and Fries later formalized in his 2015 theory, that theta oscillations from higher regions can reset the phase of gamma activity in lower cortical areas (See Figure 1), thereby organizing the timing of inputs (Fries, 2015; Bosman et al., 2012). This reset mechanism does three things: (1) aligns the excitability phases of receiving neurons, (2) resets the ongoing gamma phase, and (3) enables faster gamma rhythms to propagate more effectively to higher areas. These principles form the foundation for the Clock-and-Data model developed later in this report.

3 Connectivity of FEF and IFJ

FEF and IFJ are anatomically distinct frontal regions, and growing evidence suggests they differ functionally in their preferred communication frequencies. A resting-state MEG study shows that FEF primarily couples with dorsal visual areas via beta- and gamma-band activity, while IFJ shows stronger delta- and gamma-band connectivity with ventral visual areas (Soyuhos and Baldauf, 2022; Baldauf and Desimone, 2014).

FEF connections. Located in the posterior dorsolateral prefrontal cortex (pDLPFC; See Figure 2), FEF sits near the premotor cortex and plays a central role in spatial attention. It shows strong beta-phase coupling with the superior parietal lobule (SPL), consistent with its function in directing attention along the dorsal stream. Veniero et al. (2021) demonstrated that rhythmic TMS over right FEF at 12–20 Hz entrains beta oscillations in occipital cortex, particularly visual area V5, enhancing phase-specific excitability and causing visual performance to fluctuate at the same frequency (Veniero et al., 2021). This supports the idea that FEF uses beta-band communication as a selective frequency channel for downstream spatial attention.

IFJ connections. The Inferior Frontal Junction (IFJ) is located ventrally of the FEF at the intersection of the inferior frontal sulcus and the precentral sulcus (See Figure 2). It coordinates object-based attention and interacts preferentially with the ventral visual stream. Soyuhos et al. (2022) showed that FEF connects to dorsal regions, while IFJ shows dominant interactions with ventral areas. Importantly, IFJ can be subdivided into functionally distinct subregions: anterior IFJa and posterior IFJp (Soyuhos and Baldauf, 2022; Bedini et al., 2023)

IFJa couples with inferior and middle temporal areas in the delta and gamma bands. In contrast, IFJp shows alpha- and beta-band connectivity with FEF, and weak, inconsistent links with ventral areas. It also exhibits theta-band directionality toward both FEF and IFJa, particularly in the left hemisphere, suggesting a possible role in coordinating theta-coupling in both regions. Notably, directed alpha-band connectivity from right IFJp to right FEF is especially strong (Soyuhos and Baldauf, 2022).

These patterns suggest that IFJp may serve as a relay that coordinates timing between FEF and IFJa, rather than directly influencing posterior regions. Frequency-specific dissociation of beta- and delta-bands helps to minimize cross-talk (See Fig-

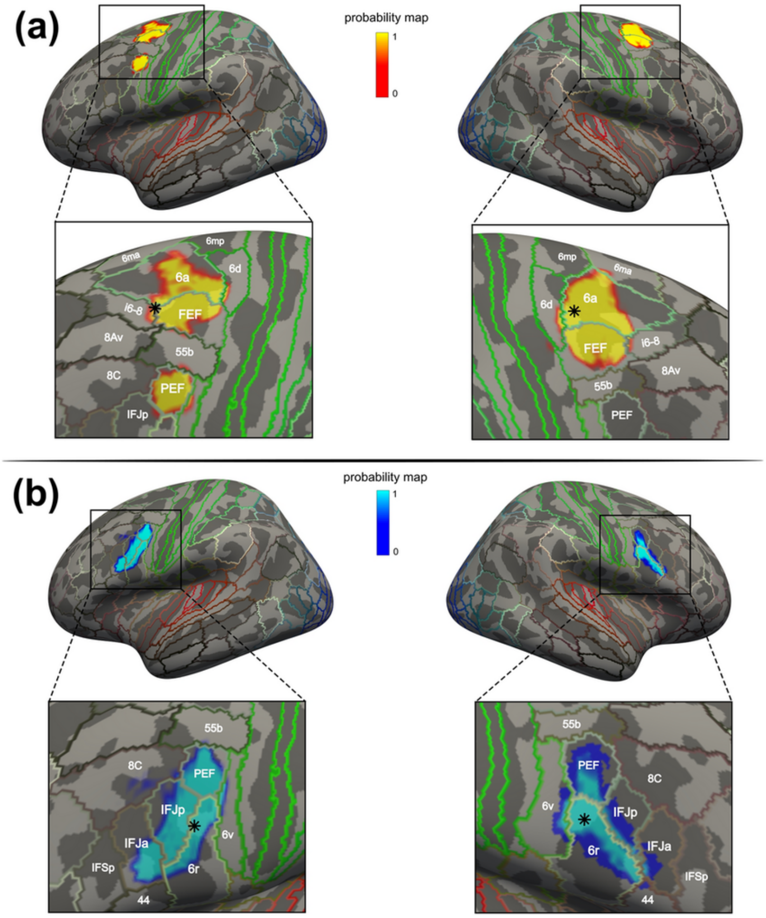


Figure 2: Localization of FEF and IFJ from an fMRI meta-analysis (Bedini et al., 2023). According to the MMP1 atlas, the Frontal Eye Field (FEF) is localized at the junction of the superior precentral sulcus (sPCS) and the superior frontal sulcus (SFS), with peaks situated in areas i6-8 and 6a. The Inferior Frontal Junction (IFJ) lies at the intersection of the inferior precentral sulcus (iPCS) and the inferior frontal sulcus (IFS), with ALE peaks in ventral 6r, Only area 55b anatomically separates thee FEF and IFJ.

ure 4), especially where both streams converge, such as in V4. Theta-band signals from IFJp to both hubs may act as a temporal alignment mechanism, enabling top-down control through temporal separation.

4 Top-Down Phase-Resets

Top-down control depends not only on anatomical connections but also on the precise timing of oscillatory signals between frontal and posterior regions. Brief stimulation, as in the TMS modulation of V5 mentioned above (Veniero et al., 2021), not only resets beta-band activity but also induces cyclic fluctuations in visual performance at the same frequency showing attentional rhythms.

If beta-band resets guide spatial information, then slower rhythms may coordinate when those resets occur (Fries, 2015). Raposo et al. (2023) found that theta-band sampling was selectively disrupted in patients with prefrontal lesions, whereas parietal damage impaired alpha/beta dynamics. This double dissociation suggests that the PFC plays a an important role in leading theta rhythms (Raposo et al., 2023).

Theta oscillations could serve as temporal gates that organize faster rhythms across areas. Fiebelkorn and Kastner (2019) propose that spatial attention fluctuates rhythmically in the theta-band, aligning with behaviorally relevant input (Fiebelkorn and Kastner, 2019). Bosman et al. (2012) further showed that coherence between V1 and V4 in the gamma band is modulated by a 4 Hz theta rhythm, showing that theta phase controls the timing of gamma communication (Bosman et al., 2012).

5 Clock-and-Data Hypothesis

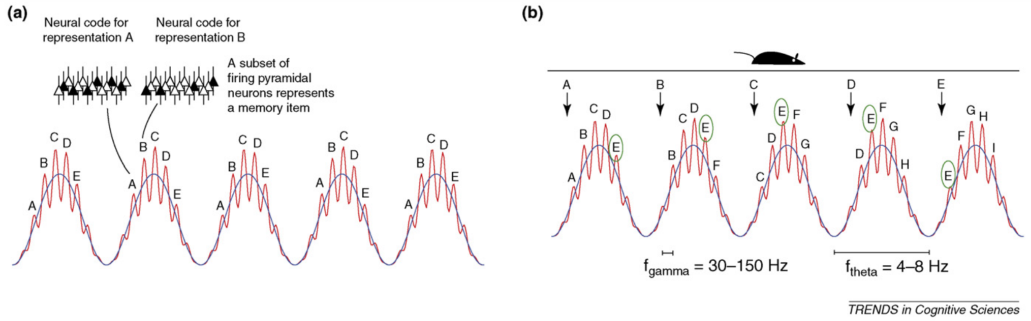
The Clock-and-Data Hypothesis proposes that a prefrontal theta rhythm temporally organizes the routing of attention signals through FEF and IFJ by assigning them distinct windows within each theta cycle. Specifically, beta-band signals from FEF and delta-band signals from IFJa may be aligned to different phases of the same theta oscillation. This mechanism would allow the brain to transmit spatial and object-based information in parallel while minimizing interference (Raposo et al., 2023; Jensen and Colgin, 2007).

A likely candidate for this timing structure is cross-frequency coupling (CFC), in which slower rhythms coordinate the timing of faster ones. Jensen and Colgin (2007) describe how theta rhythms can modulate the amplitude and timing of beta and gamma bursts across brain areas (See Figure 3a), forming temporally organized information chunks (Jensen and Colgin, 2007). Applying this principle to attention, the theta cycle could act as a "clock" that sequences spatial and object-based "data" streams. In the CTC framework, gamma-band activity is commonly associated with bottom-up or feedforward signals arising from early sensory input (Fries, 2015). These fast oscillations carry what I term the "data" from downstream areas, which must be routed and coordinated by top-down control signals - our "clock" in the PFC (Raposo et al., 2023).

An analogy comes from the hippocampal navigation system. Robinson et al. (2024) demonstrated that the medial septum serves as a theta pacemaker, temporally structuring grid and place cell activity through phase precession (See Figure 3b). Disrupting this source impairs rhythmic encoding and spatial representation (Robinson et al., 2024). A similar mechanism may apply to attention: a frontal theta rhythm could pace IFJp, which in turn relays phase-aligned signals to FEF and IFJa. This hierarchical organization would allow theta to temporally coordinate parallel attention streams.

Importantly, an intracranial study provides direct support for this logic. Sweeney-Reed et al. (2015) demonstrated that theta phase alignment between the anterior thalamus and medial PFC predicts memory encoding, and that cross-frequency coupling between theta and gamma rhythms in the anterior thalamus plays a causal role in this process. This suggests that theta coordination between PFC and thalamus can provide a theta-oscillation supporting higher-order cognition, consistent with the hypothesized role of frontal theta rhythms in organizing attention streams.

These findings raise the possibility that theta oscillations involved in attentional coordination may not be generated solely within prefrontal cortex. Instead, they may originate subcortically, possibly in the anterior or mediodorsal thalamus, and propagate via thalamo-cortical projections to anterior PFC. From there, a prefrontal relay could distribute phase-structured signals to downstream cortical targets such as IFJ and FEF. While this account remains speculative, it is consistent with recent evidence of thalamo-prefrontal theta phase coupling during memory formation (Sweeney-Reed et al., 2015) and aligns with known anatomy of cortico-thalamic loops.



TRENDS in Cognitive Sciences

Figure 3: Cross-frequency models of theta–gamma interactions. (a) In working memory, sequential gamma bursts within a theta cycle encode distinct memory items. (b) In hippocampal phase precession, advancing spatial representations are recalled in compressed gamma sequences, each aligned to a specific theta phase. In both cases, theta acts as a temporal scaffold for multiplexed coding (Jensen and Colgin, 2007).

This hierarchical relay model offers several testable predictions. If the anterior prefrontal cortex is disrupted, for example via TMS, theta-driven coordination across the attention network should be significantly impaired. Disrupting thalamic might cause an even stronger breakdown of theta-signals, given its important role in initiating or entraining the theta rhythm. In contrast, inhibiting IFJp should only delay, but not stop, the phase alignment between FEF and IFJa. Also, if FEF and IFJa are indeed structured by a shared theta oscillator, both should show phase precession in relation to IFJp or PFC.

Although highly speculative due to a lack of empirical testing, the Clock-and-Data hypothesis could offer a promising framework that, if supported by evidence, could help explain how the brain coordinates multiple attention streams in parallel.

6 Empirical Framework and Metrics

Theta phase precession. This is a phenomenon observed in the hippocampus where the firing of neurons, such as place or grid cells, systematically shifts to earlier phases of the ongoing theta cycle as an animal moves through space (See Figure 3b). This creates a temporal sequence of activations within each theta cycle, effectively allowing the brain to “replay” or organize a spatial path in a temporally ordered manner (Robinson et al., 2024; Jensen and Colgin, 2007)

If similar phase precession were found in attention-related regions like FEF and IFJa, it would suggest that the timing of their outputs is not random, but aligned to specific phases of a shared theta rhythm. This would strongly support the Clock-and-Data Hypothesis. Observing such precession would imply that attention streams are not just anatomically separated, but also temporally sequenced in a predictable, rhythmic manner.

To further test the Clock-and-Data hypothesis, I propose the use functional metrics described by Soyuhos et al. (2022) in Figures 5, 4 to assess whether theta rhythms coordinate frequency-specific communication between frontal attention hubs (Soyuhos and Baldauf, 2022).

Functional Connectivity Metrics. To show how FEF and IFJa interact with other brain areas across frequency bands (See Figure 4), we use three metrics: oPEC, iCOH, and dwPLI, following Soyuhos et al. (2022).

oPEC (Orthogonalized Power Envelope Correlation) measures amplitude-based cofluctuations between regions while correcting for volume conduction by orthogonalizing time series before computing correlations. It captures slow, envelope-based synchrony and reveals large-scale network engagement (Hipp et al., 2012).

iCOH (Imaginary Part of Coherency) isolates time-lagged, directionally relevant phase relationships between signals by ignoring zero-phase-lag interactions, thus reducing false correlations due to volume conduction (Sander et al., 2010).

dwPLI (Debiased Weighted Phase Lag Index) quantifies the consistency of non-zero phase differences while correcting for bias and down-weighting unclear connections. It provides a measure of directional phase-based coupling (Jiang et al., 2024).

Relevance to Hypothesis. Together, these metrics provide a complementary view on the amplitude and timing of communication. oPEC identifies which regions co-activate over time; iCOH and dwPLI reveal whether these interaction are directional and phase-consistent. If theta phase in anterior PFC, thalamus or IFJp predicts beta activity in FEF and delta activity in IFJa, this would support the core claim that theta rhythm gates parallel attention streams. Observing systematic theta phase precession across trials would further support this interpretation.

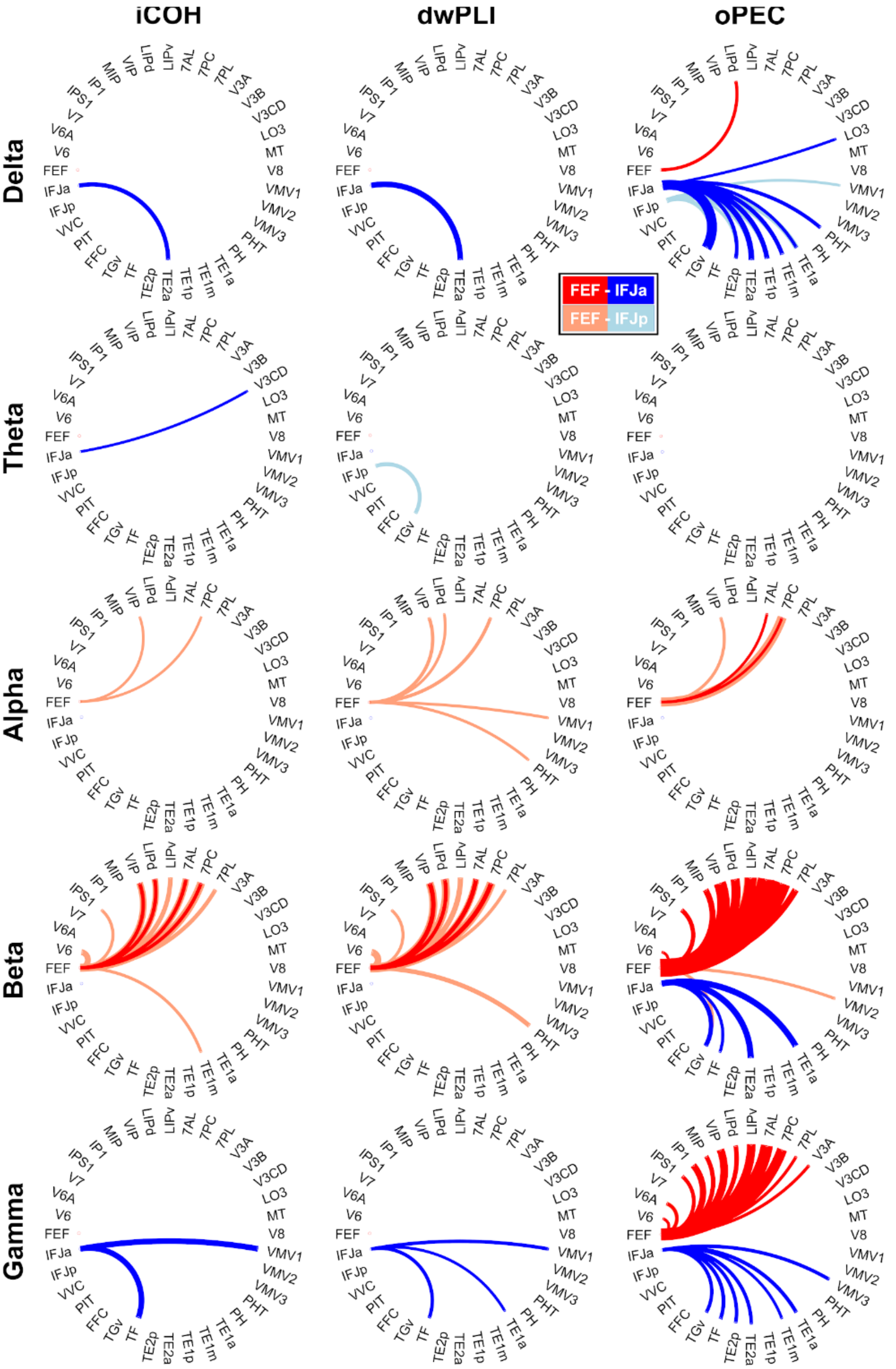


Figure 4: Frequency-specific predominant functional connectivity patterns of FEF, IFJa, and IFJp. The width of a line reflects its relative z-score of the connectivity to other nodes (Soyuhos and Baldauf, 2022).

7 Discussion

This report outlines a frequency-based model of attentional control in which theta rhythms may coordinate the routing of spatial and object-based signals through FEF and IFJ. The Clock-and-Data hypothesis suggests that a potential thalamo-prefrontal theta pacemaker could temporally separate beta and delta activity from FEF and IFJa. This mechanism may help prevent crosstalk and enable parallel processing. The relay function of IFJp could support this coordination through phase alignment.

7.1 Implications

If supported by future evidence, this model would link anatomical connectivity to temporal coordination mechanisms. The idea that theta phase provides a temporal reference frame inspired from findings about hippocampal navigation and working memory, where rhythmic theta-precession supports temporal organization. As Robinson et al. (2024) show, the medial septum provides theta-based phase structure to grid and place cell firing. A similar principle may apply to the attention system, with a prefrontal theta rhythm temporally segmenting information streams (Robinson et al., 2024).

The hypothesis integrates the frequencies beta/gamma for spatial and delta/gamma for object-based attention with a hierarchical timing structure. This perspective aligns with the view that oscillatory dynamics are not merely epiphenomenal but may shape communication through selective synchronization (Fries, 2015). However, this hypothesis requires empirical validation.

7.2 Limitations

Several foundational assumptions of the Clock-and-Data model remain speculative. The anatomical origin of the theta pacemaker is still uncertain. While IFJp shows theta-band directionality, this alone does not provide evidence that the theta rhythm in IFJ originates from a dedicated pacemaker in the prefrontal cortex or thalamus. Furthermore, it has not yet been demonstrated that FEF and IFJ exhibit rhythmic activity, such as theta phase precession, in the manner proposed by the hypothesis.

Also, whether attention operates in strictly rhythmic pulses is still being debated. Brookshire (2022) questions the rhythmic sampling hypothesis, proposing that observed periodicity may emerge from aperiodic temporal structures. In analyzing several datasets, Brookshire found that modeling data as rhythmic can lead to false conclusions if baseline fluctuations are not properly accounted for. This raises the possibility that theta-aligned signaling reflects artifacts in analyses rather than genuine neural rhythms (Brookshire, 2022).

Nevertheless, theta-aligned modulations of attention have been observed in several species and experimental contexts, especially under top-down control. This suggests that rhythmicity may emerge under specific cognitive demands and could serve as a supportive mechanism for attentional signals.

8 Conclusion

This report has proposed the Clock-and-Data hypothesis for understanding how spatial and object-based attention may be temporally coordinated via frequency-specific oscillations. Inspired from the Communication-Through-Coherence framework, hippocampal phase coding, and recent MEG and TMS studies, the hypothesis suggests that a theta pacemaker structures beta- and delta-band signals from FEF and IFJa into non-overlapping temporal windows.

This speculative model integrates anatomical and temporal dimensions of attention control. It offers an idea of how parallel information streams may avoid interference through rhythmic gating. Additional, it generates concrete predictions that can be empirically validated.

If proven, this model would highlight theta rhythms as a coordinating system that allows the brain to integrate “what” and “where” without getting in its own way.

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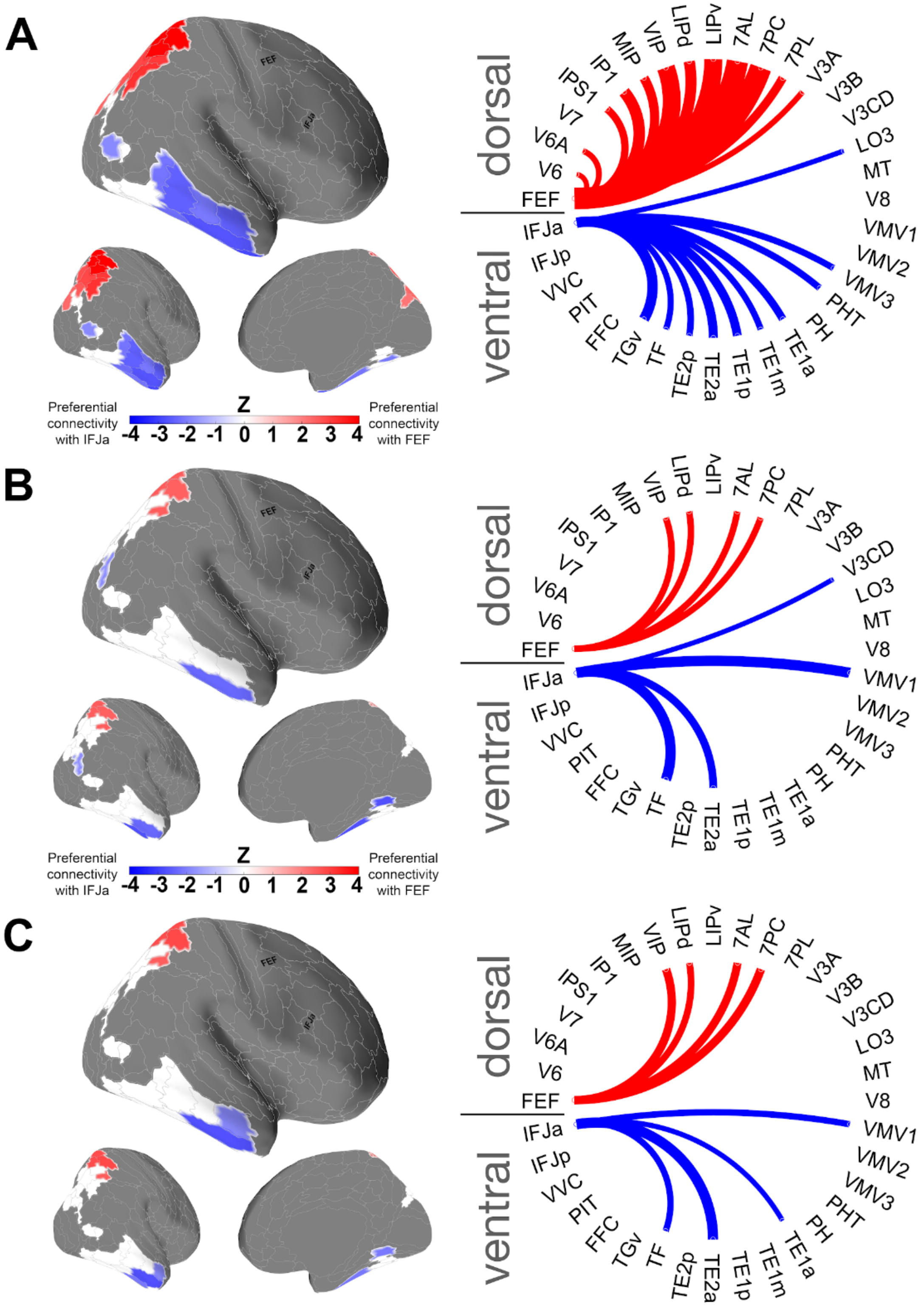

Figure 5: Functional connectivity maps of FEF and IFJa across frequency bands and hemispheres for (A) oPEC, (B) iCOH, and (C) dwPLI metrics (two-sided Wilcoxon signed-rank test, p ¡ 0.05, FDR-corrected for 33 ROIs) (Soyuhos and Baldauf, 2022).