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Spatial and Temporal Precision in Whole-Brain Mapping via Simultaneous EEG–FONI Recordings*

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Abstract

Electroencephalography (EEG) and fast optical neuroimaging (FONI) provide complementary perspectives on brain activity: EEG measures neurogenic activity at millisecond-scale temporal resolution, whereas FONI, by frequency-domain functional near-infrared spectroscopy (FD-fNIRS), captures spatially localized hemodynamic responses. To fully exploit these advantages, both modalities should ideally be recorded simultaneously. However, it remains unclear whether the same neural events can be consistently identified in both signals. Here, we simultaneously recorded 64-channel EEG and 64-channel FONI signals from a healthy control participant during closed-eyes resting state. Datasets were band-pass filtered to isolate the alpha frequency range (8–12 Hz), a rhythm linked to functional integration and cognitive processing. We then computed the Pearson correlation coefficient between every EEG channel and every fNIRS channel, yielding a 64×64 correlation matrix. Statistical analysis revealed significant cross-modal correlations for specific channel pairs ($p < .01$), indicating that alpha-band neuronal activity is reliably associated with localized hemodynamic responses in these regions. These preliminary results support the view that combined EEG–FONI recordings can deliver both the temporal precision of EEG and the spatial specificity of FD-fNIRS. The observed coupling underscores the potential of multimodal approaches to investigate neurovascular dynamics with high spatio-temporal fidelity.

Keyphrases

Non-invasive neuroimaging; frequency domain functional near-infrared spectroscopy; fast optical neuroimaging; EEG; correlation.

Introduction

Electroencephalography (EEG) is a non-invasive neuroimaging technique that records the brain's electrical activity via scalp electrodes, primarily capturing synchronized postsynaptic potentials from cortical pyramidal neurons. These potentials produce voltage fluctuations over a broad frequency range, offering millisecond-level temporal resolution that is well suited for investigating dynamic neural processes underlying sensory, cognitive, and motor functions. However, EEG's spatial resolution is limited by the diffusion of electrical fields through brain tissue, skull, and scalp, necessitating integration with other modalities for improved source localization.

Functional near-infrared spectroscopy (fNIRS), in contrast, is an optical neuroimaging method that measures cerebral hemodynamic changes by detecting the absorption of near-infrared light (650–950 nm) by oxygenated (HbO) and deoxygenated (HbR) hemoglobin in cortical regions. Using light sources and detectors placed on the scalp, fNIRS infers neural activity through neurovascular coupling, providing spatial resolution on the centimeter scale despite slower temporal dynamics associated with the seconds-long hemodynamic response. The use of frequency-domain functional near-infrared spectroscopy—referred to as FONI, i.e. fast optical neuroimaging (Gratton and Fabiani 2010; Fantini and Sassaroli 2020; Mohammad et al. 2021)—extends further the robustness to motion artifacts and compatibility with multimodal recordings at high temporal resolution.

Combining EEG and FONI yields complementary insights into brain function by integrating EEG's temporal precision with fNIRS's spatial specificity, enabling a more comprehensive characterization of neurovascular interactions. Previous work has demonstrated broad associations between these modalities, including concurrent recordings in several contexts (Chiarelli et al. 2017), activation patterns in language processing (Wallois et al. 2012), and resting-state alpha-band correlations (Moosmann et al. 2003). More recent studies highlight the promise of hybrid EEG–fNIRS approaches for brain-state decoding, such as motor imagery and vigilance monitoring, where global fNIRS signals correlate with EEG alpha activity (Chen et al. 2020). Additionally, multimodal analyses have revealed relationships between hemodynamic responses and brain oscillations, particularly in the alpha band during task performance (AL-Quraishi et al. 2021).

Despite these advances, the precise temporal correspondence between transient EEG events and fNIRS-derived hemodynamic responses remains insufficiently understood. This study focuses on alpha-band activity (8–12 Hz), a key neural rhythm implicated in functional integration, to determine whether transient alpha events detected by EEG co-occur with characteristic hemodynamic signatures in fNIRS. By adopting a hybrid EEG–FONI framework, we aim to deepen understanding of neurovascular coupling mechanisms at cortical level.

Methods

Simultaneous EEG and FONI recordings were analyzed to investigate alpha-band dynamics. The initial 5 s of each recording were excluded to

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minimize non-stationarities, yielding 2 min of usable data per session.

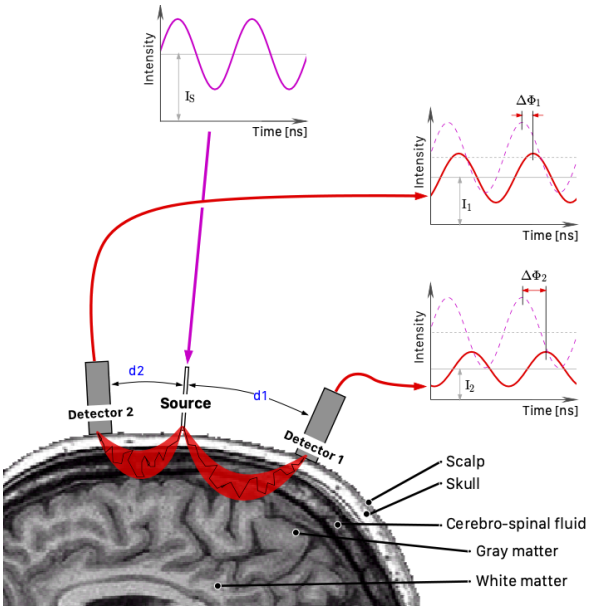

Figure 1: The phase-shift between the light emitted by the source (dotted line in the insets on the right) and the signal captured by the detectors (full lines in insets) depends on the amount of deoxygenated hemoglobin along the curved path travelled by the infra-red beam. Adapted from Pinti et al. (2020)

For FONI (Figure 1), signals from each source–detector pair were expressed as complex numbers of the form $e^{i\varphi}$, where φ denotes the phase difference, preserving the circular properties of the data and avoiding boundary discontinuities. EEG data consisted of voltage time series from scalp electrodes. Signals from both modalities were segmented into non-overlapping 1 s windows. Within each window, alpha-band power (8–12 Hz) was computed for each EEG channel using spectral analysis, producing a time series of power estimates. For FONI, the phase-derived signals recorded by FD-fNIRS were processed to extract features reflecting slow hemodynamic modulations potentially associated with alpha-band envelopes. This procedure produced, for each modality, a 124-component vector characterizing alpha-related activity across consecutive seconds.

EEG alpha-power time series were averaged across electrodes to obtain a mean temporal profile. Pearson correlations were then calculated between this mean EEG alpha power and the time series from individual FD-fNIRS channels (e.g., D1). Statistical significance was assessed at $p < .005$. EEG electrodes showing strong correlations with the selected fNIRS channel ($p < .01$) were identified. Analyses incorporated temporal lags (e.g., a 1 s delay in FONI relative to EEG) to account for the hemodynamic response latency. Spatial maps of significantly correlated electrodes were generated to evaluate co-localization with the optical measurement sites.

This approach is consistent with established multimodal integration protocols, including canonical correlation analysis variants for EEG–fNIRS data fusion (Zhuang et al. 2020) and graph-theoretic comparisons of network structure (Blanco et al. 2024).

Results

Correlation analysis revealed significant associations between EEG alpha power and fNIRS signals. A representative fNIRS channel (D1) showed a robust correlation with the averaged EEG alpha power ($p < .005$), with the peak correlation occurring when the fNIRS signal lagged EEG by 1 s—consistent with the expected delay from neurovascular coupling (Figure 2). The EEG electrodes most strongly correlated with D1 ($p < .01$) were predominantly located over frontal regions, spatially aligning with the fNIRS optical measurement path. These results indicate that transient EEG alpha bursts are followed by delayed, co-localized hemodynamic responses.

At a temporal resolution of 1 s, the observed associations are attributable to slow fluctuations in the alpha-power envelope rather than to rapid oscillatory cycles. Positive correlations between changes in HbO concentration and alpha-band power were localized to specific cortical regions, consistent with spatial patterns reported in task-based investigations (Su et al. 2023). Collectively, these findings support the utility of hybrid EEG–fNIRS approaches for characterizing neural–hemodynamic interactions in resting-state conditions, complementing previous work linking fNIRS global signal amplitudes to EEG vigilance measures (Chen et al. 2020).

Discussion

The present study provides evidence that transient alpha-band oscillations in EEG are systematically coupled with localized, delayed hemodynamic responses captured by FD-fNIRS, reinforcing the potential of multimodal approaches for mapping brain dynamics with high spatio-temporal precision. This cross-modal correspondence aligns with earlier work demonstrating low-frequency covariation between electrophysiological rhythms and vascular signals (Moosmann et al. 2003; Yuan et al. 2012), and extends these findings by focusing on resting-state conditions where intrinsic fluctuations, rather than task-evoked responses, dominate neural activity. The observed 1-second lag between EEG and fNIRS signals is consistent with canonical neurovascular coupling delays (Buxton et al. 2004; Obrig et al. 2000), lending physiological plausibility to the results.

Importantly, our findings highlight the value of examining slow modulations in oscillatory power envelopes rather than attempting to align rapid neural oscillations directly with slower hemodynamic processes. This approach parallels strategies in simultaneous EEG–fMRI studies, where correlations with BOLD signals are more readily observed in the amplitude envelopes of specific frequency bands (Mantini et al. 2007; Laufs et al. 2003). By leveraging FD-fNIRS's enhanced motion robustness and phase-based sensitivity (Fantini and Sassaroli 2020), the current framework offers improved stability for long-duration recordings and potential suitability for ecologically valid, real-world monitoring scenarios.

Beyond methodological considerations, these results have implications for applied neuroscience domains such as brain–computer interfaces (BCIs), neurorehabilitation, and cognitive workload monitoring. Hybrid EEG–fNIRS BCIs have already shown improved classification performance in motor imagery and vigilance tasks (Fazli et al. 2012; AL-Quraishi et al. 2021), and our approach could be adapted to enhance decoding of resting-state brain states or transitions between cognitive modes. The demonstrated spatial specificity in alpha-related hemodynamic changes could also be leveraged for targeted neurofeedback interventions, where both electrophysiological and hemodynamic

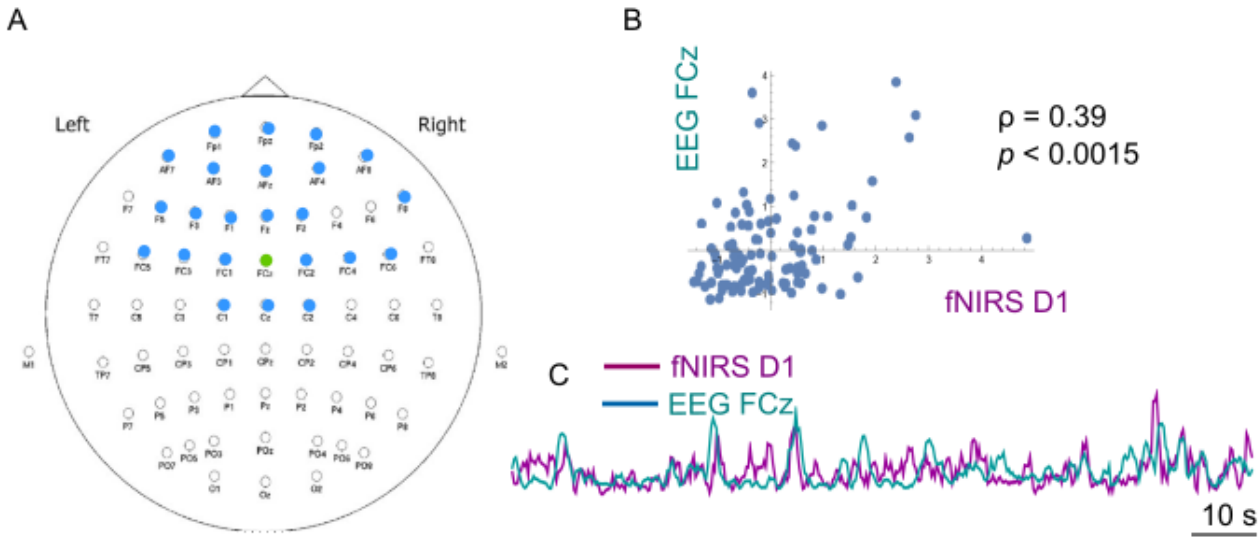

Figure 2: A. Collection of EEG electrodes (blue and green) the alpha power of which is significantly correlated with the FD-fNIRS signal D1. The signal of the EEG electrode marked in green is used in correlated with the optical signal in panels B and C. B: Normalised amount of alpha power registered by the fNIRS detector D1 (x axis) and the EEG FCz electrode (y axis) in non-overlapping 1-second temporal windows. A positive and significant correlation is observed. C: Temporal evolution of the normalised alpha power contained in the two signals of panel B. A certain degree of congruence in the epochs with large alpha power can be discerned.

parameters are modulated in tandem.

However, several limitations warrant consideration. First, the single-subject design limits generalizability and calls for replication across larger, demographically diverse samples. Second, our analysis was restricted to the alpha frequency band; expanding to other rhythms (e.g., theta, beta) could reveal frequency-specific patterns of neurovascular coupling relevant to different cognitive processes. Third, residual physiological artifacts (e.g., systemic blood flow fluctuations) may contribute to observed correlations despite preprocessing. Incorporating short-separation fNIRS channels, advanced artifact removal algorithms, and physiological covariates (e.g., heart rate, respiration) could improve specificity. Finally, our analyses focused on univariate correlations; future work employing network-level graph analyses (Blanco et al. 2024) or data-driven fusion techniques (Zhuang et al. 2020) may uncover richer patterns of structure–function relationships.

Conclusion

This preliminary investigation into EEG–FONI integration during resting-state alpha-band activity reveals significant cross-modal correlations, affirming the presence of reliable neurovascular coupling at specific cortical sites. By demonstrating that transient EEG alpha bursts are associated with delayed, spatially co-localized hemodynamic responses in FD-fNIRS, our findings validate the complementary strengths of these modalities: EEG's millisecond temporal precision and FD-fNIRS's centimeter-scale spatial resolution. This hybrid approach not only bridges electrical and optical measures of brain function but also underscores the potential for enhanced spatio-temporal fidelity in whole-brain mapping, aligning with emerging multimodal neuroimaging paradigms.

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Contributions

All authors contributed equally to the paper.

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