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A Cross-disciplinary Review of fNIRS-EEG Dual-modality Neuroimaging Systems

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Introduction

The human brain is a highly complex organ, and understanding its structure, function, and dynamics requires tools that can capture both its electrical and hemodynamic activity with high precision. Among the most promising approaches in contemporary neuroimaging is the integration of functional Near-Infrared Spectroscopy (fNIRS) and Electroencephalography (EEG), forming a dual-modality system that leverages the complementary strengths of each technique. EEG offers excellent temporal resolution by directly measuring neuronal electrical activity, making it ideal for capturing fast brain dynamics such as event-related potentials or seizures. In contrast, fNIRS provides valuable spatial information about cerebral blood flow and oxygenation by detecting changes in oxy- and deoxyhemoglobin concentrations, albeit with lower temporal precision. When combined, fNIRS-EEG systems offer a more holistic view of brain function, enabling researchers and clinicians to investigate the neurovascular coupling that links neural activity with cerebral hemodynamic [1].

Description

The integration of fNIRS and EEG in a single neuroimaging framework addresses a key limitation of standalone modalities: EEG's poor spatial resolution and fNIRS's lower temporal fidelity. The dual-modality system achieves synergistic insight by combining the millisecond-level temporal resolution of EEG with the spatially resolved hemodynamic mapping of fNIRS, thus enabling simultaneous capture of electrical activity and its associated blood flow changes. Technologically, this integration involves combining optical sensors and electrical electrodes in a single wearable or cap-based device, with careful considerations for mutual interference, signal quality, and synchronization. Advances in materials science, signal processing, and wireless technology have made it increasingly feasible to design lightweight, mobile fNIRS-EEG systems that maintain high data fidelity. One of the primary challenges in dual-modality systems lies in the co-registration of data streams that differ in sampling frequency, signal type, and physiological origin. To address this, researchers have developed hybrid signal processing pipelines that include artifact rejection algorithms, feature fusion models, and machine learning techniques for data interpretation [2].

Importantly, the growing interest in personalized and portable neuroimaging has catalysed the development of user-friendly, miniaturized systems capable of real-time data transmission and cloud-based analytics. Multidisciplinary collaborations among engineers, neuroscientists, data scientists, and clinicians have accelerated innovations in both hardware and software. These include dry electrode EEG systems that minimize skin preparation, and fNIRS modules that use LED sources and silicon photo detectors for improved signal-to-noise ratio. Software frameworks that enable multimodal data synchronization, like Lab Streaming Layer (LSL), and platforms for real-time neuro feedback have enhanced the utility of these systems in longitudinal and at-home studies. Ethical considerations around data privacy, especially in wearable cognitive monitoring, are also being actively discussed in parallel with technological development. In educational and developmental studies, fNIRS-EEG systems are increasingly used to assess learning processes and attention regulation in children in real-time without requiring sedation or invasive procedures [3]

This dual-modality approach has gained significant attention across disciplines neuroscience, psychology, biomedical engineering, cognitive science, and clinical medicine due to its potential in fundamental brain research and real-world applications such as Brain-Computer Interfaces (BCIs), neuro rehabilitation, mental workload assessment, and epilepsy monitoring. Furthermore, the non-invasive, portable, and relatively cost-effective nature of both EEG and fNIRS makes their integration suitable for use in naturalistic and bedside environments, including neonatal units, sports settings, and educational research. This review aims to provide a cross-disciplinary synthesis of the development, technical challenges, methodological innovations, and emerging applications of fNIRS-EEG dual-modality systems, exploring how this strategic integration is shaping the future of multimodal neuroimaging. For instance, EEG can detect abnormal neural discharges while fNIRS maps localized blood flow responses, offering a comprehensive assessment of cerebral dysfunction. Moreover, this system has been instrumental in developing adaptive BCIs where brain signals are used to control external devices in real time important for patients with motor impairments or locked-in syndrome. The dual-modality approach also facilitates more accurate workload and stress monitoring in occupational and aviation psychology by linking cognitive performance with both neural and vascular responses [4].

Furthermore, the dual-modality system provides insights into neurovascular coupling a fundamental process disrupted in many neurological diseases. Studies leveraging this approach have revealed novel patterns in coupling dynamics during tasks, rest, and disease states, informing not only basic neuroscience but also computational modelling of brain function. Despite the promise, limitations remain particularly in terms of spatial resolution in deeper brain structures, sensitivity to motion artifacts, and the interpretability of multimodal data. Nonetheless, on-going research is exploring the use of artificial intelligence, source localization algorithms, and machine learning classifiers to improve data interpretation, increase robustness, and create individualized brain activity profiles Future directions point toward even more integrated systems involving additional modalities such as functional MRI, transcranial stimulation, and magneto encephalography, as well as the inclusion of AI-driven analytics for real-time brain state decoding. The challenges of multimodal data fusion, artefact removal, and interpretability will likely be met with continued methodological innovations and computational tools. Ultimately, the fNIRS-EEG dual-modality system exemplifies how strategic technological convergence can overcome individual modality limitations, unlocking new frontiers in understanding the brain and transforming how we measure, monitor, and interface with human cognition in health and disease [5].

Conclusion

The fNIRS-EEG dual-modality imaging system represents a paradigm shift in neuroimaging, offering a powerful, non-invasive approach to simultaneously assess the brain's electrical and hemodynamic activity. Its strategic integration bridges the gap between two fundamentally different but complementary modalities, enabling a richer, more nuanced understanding of brain function across a spectrum of contexts from laboratory research to clinical diagnostics

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and real-world applications. The versatility of this system lies in its ability to be applied across disciplines, ranging from cognitive neuroscience to rehabilitation engineering and human-computer interaction. As technological advancements continue to reduce barriers related to signal quality, portability, and data complexity, the dual-modality framework is poised to play an increasingly central role in multimodal brain research. Its application in monitoring dynamic brain states, diagnosing neurological disorders, optimizing human performance, and enabling intuitive BCIs reflects the system's vast potential. Importantly, the fNIRS-EEG combination also encourages a new kind of research collaboration one that is inherently cross-disciplinary, drawing from neuroscience, optics, electrophysiology, data science, and clinical medicine.

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Conflict of Interest

There are no conflicts of interest by author.

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