Neuroergonomic Evaluation of a P300 Speller BCI Using Simultaneous EEG and fNIRS

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Synopsis

Brain-computer interfaces (BCIs) can provide essential communication for people with severe motor impairments, but most systems remain limited to laboratory and short-term use. This multimodal pilot study examined mental demands during use of a P300 speller with simultaneous electroencephalography (EEG) and functional near-infrared-spectroscopy (fNIRS). Two participants completed copy-spelling tasks under easy and difficult conditions varying in stimulus repetitions and trial duration. EEG enabled real-time target classification using stepwise linear-discriminant-analysis (SWLDA), while fNIRS monitored prefrontal oxygenation changes as correlates of cognitive workload. Preliminary findings suggest higher prefrontal workload under time-constrained conditions despite stable accuracy, informing home-deployable neuroergonomic BCI development for ALS.

Background

Brain-computer interfaces (BCIs) establish direct communication pathways between the central nervous system and external devices by translating neural signals into actionable commands, bypassing conventional motor pathways (Wolpaw et al., 2002). Among BCI paradigms, the P300 speller remains one of the most validated approaches for augmentative communication, leveraging an attention-modulated event-related potential elicited approximately 300ms after a rare, task-relevant stimulus Farwell and Donchin, 1988). Its clinical relevance, including for individuals with amyotrophic lateral sclerosis (ALS), stems from reliance on preserved attentional function rather than volitional motor output. Despite demonstrated efficacy, most P300 BCI studies have been conducted in highly controlled laboratory settings, limiting insight into usability under realistic operational demands (Kübler et al., 2014). Neuroergonomics provides a framework for addressing this gap by emphasizing cognitive workload and sustained usability as key design constraints (Parasuraman, 2011). Integrating fNIRS with EEG enables complementary assessment of mental state during BCI operation (Liu et al, 2017) and may support development of systems that are accurate, usable, and cognitively sustainable in home and clinical settings.

Methods

Two neurologically healthy participants completed the protocol using a custom python based P300 speller with 40 targets arranged in a checkerboard stimulus paradigm (Townsend et al., 2010). Task difficulty was manipulated across two counterbalanced conditions: an easy condition with 20 stimulus repetitions and a 5-second trial window, and a difficult condition with 10 repetitions and a 3-second window. Each session began with a calibration phase comprising 20 randomly ordered target characters, after which a stepwise linear discriminant analysis (SWLDA) classifier was trained on the acquired data (Krusienski et al., 2006). Participants then completed a copy-spelling task in both conditions, spelling the word "RESEARCH" followed by selection of the Enter key, yielding nine targets per sequence. EEG was recorded using Mentalab Explore Pro headset at eight channels (Fz, Cz, P3, Pz, P4, PO7, PO8, Oz), sampled at 250 Hz, and processed with 0.5–30 Hz bandpass and 60 Hz notch filters. Concurrent hemodynamic data were acquired using the fNIR Devices model 2000S device with 16 optodes at 10 Hz, operated in passive monitoring mode to continuously index cortical workload without imposing additional task demands on participants.

Results

Both participants completed calibration and then copy-spelling in both easy and difficult conditions. Selection accuracy differed substantially between participants but did not vary across conditions within participants: Participant 1 achieved 62.5% accuracy in both conditions, whereas Participant 2 achieved 100% accuracy in both conditions. SWLDA-based EEG classification supported real-time target selection in both conditions and differentiated target from non-target responses. Preliminary fNIRS observations suggested greater prefrontal hemodynamic engagement (HbO changes), particularly during the difficult condition (Figure 1), consistent with increased cognitive workload despite stable behavioral accuracy.

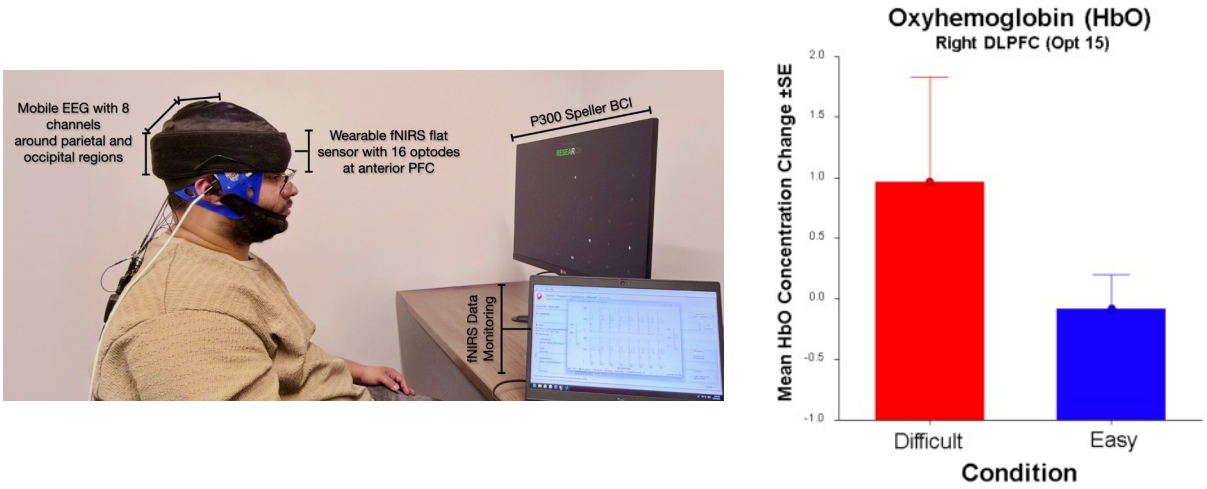

Figure 1. Left: Multi-Modal BCI experiment setting. **Right:** Significant task condition difference in HbO only at right dlPFC (Opt 15) during P300 spelling performance. The difficult condition, as expected, showed higher activity relative to the easy condition.

Discussion

This ongoing pilot study examines the neuroergonomic demands of a custom P300 speller under manipulated task difficulty using simultaneous EEG and fNIRS. While more data collection is underway, three preliminary observations are notable. First, reducing stimulus repetitions and shortening trial duration did not reduce spelling accuracy in these two participants, suggesting that shorter trial settings may be feasible in some users without immediate performance loss. Second, marked inter-individual variability in accuracy was observed, consistent with known heterogeneity in BCI performance. Third, fNIRS indicated increased cortical workload in the more time-constrained condition despite unchanged behavioral accuracy, suggesting that stable performance may be maintained at the cost of greater mental effort. Together, these findings support multimodal neuroergonomic evaluation of BCIs, as behavioral accuracy alone may not fully capture usability or user burden. Larger studies, including target clinical populations, are needed to determine how workload-sensitive metrics can inform optimization of accurate and cognitively sustainable BCI systems.

Disclosures

HA has equity in fNIR Devices LLC that licensed IP from Drexel University and manufactures optical brain imaging sensor used in the study.

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