Assessing Cognitive Workload During Dual-Task Performance: An fNIRS Study of N-Back Tasks Under Walking and Standing Conditions

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Synopsis

Brain-Computer Interfaces (BCI) have traditionally focused on detecting users' unconscious brain states in stationary positions. However, extending BCI applications to mobile scenarios involves evaluating our ability to classify mental workload during movement. Previous research has demonstrated that walking while performing complex cognitive tasks increases mental workload in the prefrontal cortex (Hoang et al., 2020). This study investigates differences in mental workload between standing and walking conditions using multiple sensor modalities designed to assess cognitive load.

Background

Previous work has shown that mental workload in the prefrontal cortex can be classified from fNIRS data using a variety of machine learning models (Russell et al., 2025). Functional Near-Infrared Spectroscopy (fNIRS) data has shown activation in the prefrontal cortex (PFC) during cognitive tasks including problem solving, planning, reasoning, and working memory (Koechlin et al., 1999; Bunce et al., 2011). Mapping activation patterns in the PFC to workload levels is a key research topic in BCI.

Methods

Participants

Nineteen participants confirmed that they met the eligibility criteria for this study. All participants did not have a history of brain injury or psychological disorder, and were not on medication affecting brain activity. Prior to the study all participants signed consent forms approved by the Social, Behavioral & Educational Research Institutional Review Board (SBER IRB) at Tufts University. Participants were given monetary compensation of $20/hr for their time. Data from 4 of the 19 participants had to be removed from analysis due to data loss.

Recording

Functional near-infrared spectroscopy (fNIRS) data was recorded using an Artinis Brite device by Artinis Medical Systems. This device records at 14 different optode locations covering the prefrontal cortex and motor cortices in the left and right hemispheres. fNIRS data was recorded using the Artnis Oxysoft software.

Electroencephalography (EEG) data was recorded using the Neuroelectrics Enobio 32 and pupil dilation data was recorded using the SMI ETG2 Eye Tracking Glasses. Due to technical failures, the data from both of these devices were unusable thus further analysis was done using fNIRS and survey data.

Surveys

The NASA Task Load Index (NASA-TLX) was used to measure subjective workload at the end of each block. The participant was asked to assess their level of mental workload after completing a single block of an n-back task at a particular difficulty (0, 1, 2). The NASA-TLX is a series of questions that targets six aspects of mental workload, each of which is on a 21-point Likert scale. The aspects of mental workload evaluated include mental, physical, and temporal demand, as well as effort, performance, and frustration.

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Experiment Design

The experiment followed a 3x2 design with three workload levels and two movement conditions. Participants stood on a treadmill facing a computer screen at a standing desk. Each block began with a fixation cross during a rest period, followed by presentation of the n-back level and movement condition. Participants completed 40 rounds of the n-back task over 90 seconds (Owen et al., 2005; Jaeggi et al., 2010). After six practice blocks covering all task combinations, participants completed 18 randomly assigned experimental blocks. A Detection Response Task (DRT) was administered concurrently during n-back performance by pressing a button in response to a vibration stimulus delivered by a smartwatch.

fNIRS Signal Processing

The Beer-Lambert law and bandpass filtering were applied through the Artinis Oxysoft software used to record fNIRS data. Baseline correction was also performed on the fNIRS data. Channels were rejected using a paired t-test with the hemodynamic response function (HRF) to keep a single channel with only the most significant changes for each ROI (Hong et al., 2018).

Statistical analysis

Normality was assessed using Shapiro-Wilk tests at each N-back level for individual channels and regions of interests. Repeated measures ANOVA was performed on HbO during standing to test n-back effects. Pairwise comparisons between standing and walking conditions at each n-back level used paired t-tests or Wilcoxon signed-rank tests depending on the normality of differences. All p-values were corrected with false discovery rate (FDR) correction for multiple comparisons (Benjamini & Hochberg, 1995).

Results

fNIRS analysis showed statistically significant results for the 0-back versus 2-back comparison on a single channel in the left frontal lobe, and a notable difference in oxygenated hemoglobin in the right frontal lobe between standing and walking conditions during the 0-back and 2-back tasks. Machine learning analysis using a Gaussian model achieved an average F1 score of 66.84% and accuracy of 50.25% on a test set which is on par with the current standard (Benerradi et al., 2023).

NASA-TLX subjective workload assessments demonstrated statistically significant increases in mental demand for both 1-back and 2-back tasks compared to baseline, though movement conditions did not affect mental demand ratings. Physical demand ratings significantly increased during walking compared to standing, but were unaffected by N-back level. Temporal demand showed significant changes based on both n-back level and movement condition independently, with no interaction effect between the two factors. Performance and effort ratings both showed statistically significant changes related to N-back level but were unaffected by walking versus standing conditions.

Discussion

This study demonstrated that cognitive workload and physical activity produce distinct physiological and subjective responses. The significant fNIRS findings in the frontal right region during varying N-back levels suggest increased prefrontal activation with higher cognitive demands, consistent with working memory literature (Koechlin et al., 1999; Owen et al., 2005).

The NASA-TLX results aligned with expectations based on previous literature and our physiological results. Mental and temporal demand increased with task difficulty and physical demand solely with the movement condition. The independence of these factors suggest cognitive and physical workload operate through separate mechanisms, although future work is necessary to confirm this. These findings support the feasibility of dual-task paradigms for studying real-world cognitive performance under physical stress, though improved signal processing and larger sample sizes may enhance classification accuracy in future work. We find that different physical conditions while completing complex cognitive tasks leads to differentiations in oxygenations which should be taken into account for mobile BCIs.

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