Measuring attentional states with whole head high density wearable fNIRS

Laura B. Carlton[1], Chi-Yuan Chang[1,2], Jessica A. Anderson[1], Aneesa D. Pathiyaparambath[1], Yasaa Mohammad[1], De'Ja Rogers[1], Mark Halko[3], David Rothlein[4], Sreekanth Kura[1], Bernhard Zimmermann[1], Emily P. Stephen[1,2], Meryem A. Yücel[1], David A. Boas[1], Alexander von Lühmann[5,6], Michael Esterman[1,4,7]

[1]Neurophotonics Center, Biomedical Engineering, Boston University, Boston, MA 02215, USA
[2]Department of Mathematics and Statistics, Boston University, Boston, MA 02215, USA
[3]Schizophrenia and Bipolar Research Program, McLean Hospital, Belmont MA, and Harvard Medical School, Boston, MA
[4]Department of Psychiatry, Boston University Chobanian and Avedisian School of Medicine, Boston, MA, USA
[5]Intelligent Biomedical Sensing (IBS) Lab, Technische Universität Berlin, 10587 Berlin, Germany
[6]BIFOLD – Berlin Institute for the Foundations of Learning and Data, 10587 Berlin, Germany
[7]National Center for PTSD, VA Boston Healthcare System, Boston, MA, USA

Synopsis

The gradCPT task has been well established to measure the neural basis of sustained attention in fMRI. Here we propose the use of this task to first validate the use of fNIRS for measuring this neural basis of sustained attention and then extend the use of the task to identify differences in hemodynamic responses depending on attentional state as suggested by recent studies in rodents. fNIRS can closely replicate the results seen in fMRI. Furthermore, relevant functional networks show distinct differences depending on the attentional state of participants.

Background

Functional magnetic resonance imaging (fMRI) has been widely used to study sustained attention due to its high spatial resolution and ability to characterize distributed neural activity. Functional near-infrared spectroscopy (fNIRS) offers complementary advantages in portability and wearability, enabling attention paradigms to be extended beyond traditional laboratory settings. Recent advances in full-head fNIRS coverage allow access to large-scale cortical functional networks.

Esterman et al. (2013) developed a gradual onset continuous performance task (gradCPT) which can be used to probe the behavioural and neural correlates underlying fluctuations in attention. During the task, images transition between city and mountain scenes every 800 ms. Participants are instructed to respond to frequent city scenes (90%) and withhold responses to infrequent mountain scenes (10%). Attentional state is quantified using the variance time course (VTC), defined as each reaction time's absolute deviation from the mean. fMRI studies have shown that slow fluctuations in the blood oxygen level dependent (BOLD) signal correlate with the VTC, revealing spatial patterns consistent with known attentional networks. The first aim of this work is to test whether fNIRS can similarly index attentional state by correlating the VTC with cortical oxyhemoglobin (HbO) signals.

Recent evidence indicates that hemodynamic response functions (HRFs) vary over time with changes in neuromodulatory signaling (Rauscher et al. 2024). Because attentional state in humans is linked to neuromodulator fluctuations, we hypothesize that HRF temporal dynamics differ across attentional states. Using the median VTC to differentiate *in-the-zone* and *out-of-the-zone* periods, the second aim is to identify state-dependent differences in HRFs in relevant cortical regions using fNIRS-evoked responses to mountain (no-go) trials.

Methods

fNIRS data were collected from 20 participants using our high density fNIRS system, termed NinjaNIRS (O'Brien et al. 2024) which provides whole-head coverage with 567 spatially overlapping dual-wavelength measurement channels. Each participant completed up to three 6-minute runs of the gradCPT task, from which the VTC was computed using reaction time data.

Data were minimally preprocessed using the Cedalion Toolbox (Middell et al. 2026) by converting intensity to optical density and then to chromophore concentrations using the modified Beer–Lambert law. HRFs were estimated with a general linear model (GLM) for correct *in-the-zone* and *out-of-the-zone* mountain trials, incorrect mountain trials, and incorrect city trials.

For the first aim, the full optical density time series were projected onto the cortical surface using standard diffuse optical tomography (DOT) methods. Cortical HbO timeseries were then correlated with the VTC to generate spatial correlation maps. These fNIRS-derived maps were compared with spatial correlation maps generated by correlating the VTC with BOLD time series from the fMRI data from 72 participants, using the 600-region Schaefer parcellation (Schaefer et al. 2018).

For the second aim, fNIRS-derived HRFs were projected onto the cortical surface using DOT and averaged within each of the 17 functional networks defined by Yeo et al. (2011) using the Schaeffer parcellation. Only the networks with adequate fNIRS sensitivity are shown. The spatial and temporal dynamics of the HRFs were then compared between correct *in-the-zone* and *out-of-the-zone* mountain trials.

Results

To validate the suitability of fNIRS for measuring attentional modulation, spatial maps of the correlation between the full HbO/BOLD timeseries and the VTC were compared between fNIRS and fMRI (Figure 1). Figure 1 shows strong spatial correspondence between the fNIRS- and fMRI-derived maps. The correlation between the spatial maps is 0.31 ($p < 0.01$). Frontal regions within the Default Mode Network (DMN) exhibited higher activity when the VTC is low as indicated by anticorrelations in the spatial maps. Conversely, task-positive regions showed greater activity

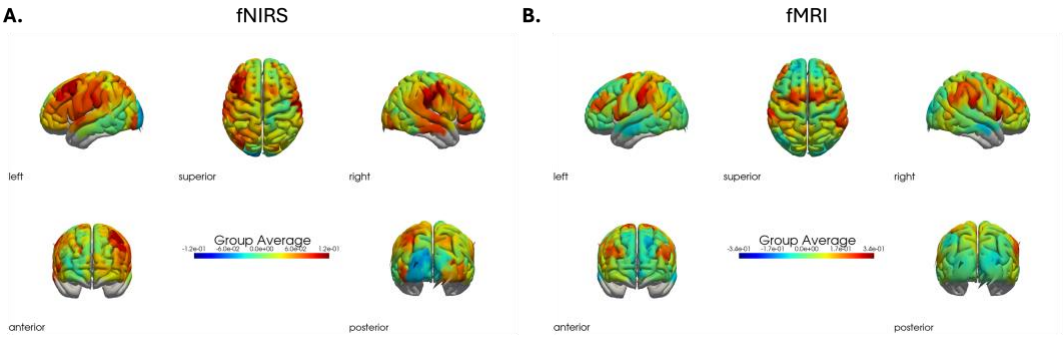

Figure 1. Group average Spearman R correlation coefficient showing the strength of the temporal correlation between the VTC and A) HbO (fNIRS) B) BOLD (fMRI) timeseries. Spatial correlation between the maps is 0.31 ($p < 0.01$).

when the VTC is high as indicated by strong positive correlations in the spatial maps.

Differences in hemodynamic response function (HRF) dynamics associated with attentional state were also observed in correct mountain trials (Figure 2). Several task-positive networks, including Dorsal Attention Network (DAN) B, Ventral Attention Network (VAN) A, and Control Network A, showed greater peak amplitudes during *out-of-the-zone* periods. Other regions exhibited more subtle or minimal differences in HRF shape between *in-* and *out-of-the-zone* states, indicating network-specific sensitivity to attentional fluctuations.

Discussion

These preliminary findings are consistent with prior fMRI studies and demonstrate the feasibility of using fNIRS to measure modulations in attentional state. There was a high degree of spatial overlap between the VTC correlation maps observed across the two modalities. Remaining differences may reflect variability in the subject populations as well as variability in regional sensitivity, as fMRI probes deeper brain structures than fNIRS, influencing the number and distribution of voxels or vertices contributing to each network.

In-the-zone periods (when the VTC is low) are associated with reduced attentional effort and more automatic, "autopilot-like" behavior, consistent with the anti-correlation between the DMN in frontal areas and the VTC (Figure 1). In contrast, *out-of-the-zone* periods are expected to engage greater task-positive processing to prevent errors, particularly within the dorsal and ventral attention networks (DAN and VAN). This pattern is reflected in both the VTC correlation maps (Figure 1), which show increased DAN activity during periods with increased VTC (likely *out-of-the-zone* periods), and the evoked HRFs, which exhibit larger amplitudes in several task-positive networks (Figure 2).

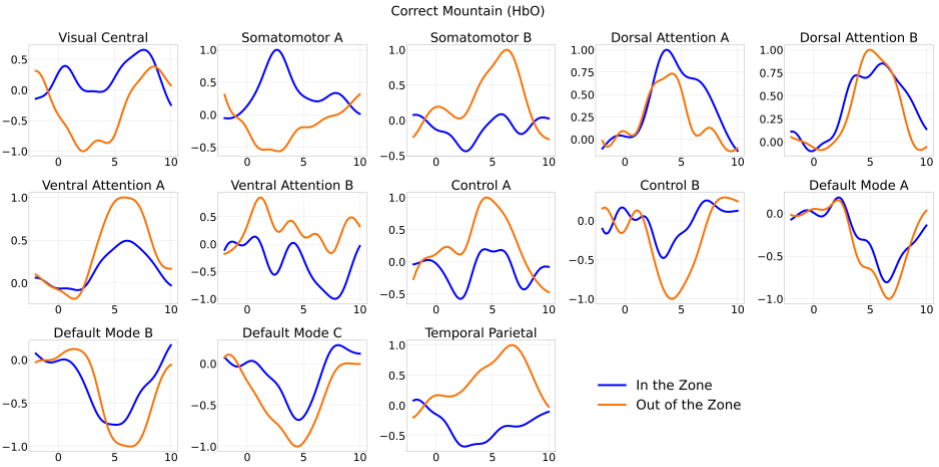

Figure 2. HbO timecourses from fNIRS corresponding to 13 of the 17 functional networks defined by Yeo et al. (2011). fNIRS HbO timecourses are shown for only correct mountain trials while in-the-zone (blue) and out-of-the-zone (orange).

References

Esterman, Michael, Sarah K. Noonan, Monica Rosenberg, and Joseph Degutis. 2013. "In the Zone or Zoning Out? Tracking Behavioral and Neural Fluctuations During Sustained Attention." *Cerebral Cortex* 23 (11): 2712–23. https://doi.org/10.1093/CERCOR/BHS261.

Middell, E., L. Carlton, S. Moradi, et al. 2026. "Cedalion Tutorial: A Python-Based Framework for Comprehensive Analysis of Multimodal fNIRS & DOT from the Lab to the Everyday World." arXiv:2601.05923. Preprint, arXiv, January 9. https://doi.org/10.48550/arXiv.2601.05923.

O'Brien, W. Joseph, Laura Carlton, Johnathan Muhvich, et al. 2024. "ninjaNIRS: An Open Hardware Solution for Wearable Whole-Head High-Density Functional near-Infrared Spectroscopy." *Biomedical Optics Express* 15 (10): 5625–44. https://doi.org/10.1364/BOE.531501.

Rauscher, Bradley C., Natalie Fomin-Thunemann, Sreekanth Kura, et al. 2024. "Neurovascular Impulse Response Function (IRF) during Spontaneous Activity Differentially Reflects Intrinsic Neuromodulation across Cortical Regions." Preprint, bioRxiv, September 15. https://doi.org/10.1101/2024.09.14.612514.

Schaefer, Alexander, Ru Kong, Evan M. Gordon, et al. 2018. "Local-Global Parcellation of the Human Cerebral Cortex from Intrinsic Functional Connectivity MRI." *Cerebral Cortex (New York, N.Y.: 1991)* 28 (9): 3095–114. https://doi.org/10.1093/cercor/bhx179.

Thomas Yeo, B. T., Fenna M. Krienen, Jorge Sepulcre, et al. 2011. "The Organization of the Human Cerebral Cortex Estimated by Intrinsic Functional Connectivity." *Journal of Neurophysiology* 106 (3): 1125–65. https://doi.org/10.1152/JN.00338.2011.