Whole-Head fNIRS Neuro-Telemetry During Simulated Racing

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Synopsis

Competitive racing simulators provide a unique neuroergonomic setting in which skilled operators repeatedly optimize performance under high cognitive and sensorimotor demands, supported by dense vehicle telemetry. Functional near-infrared spectroscopy (fNIRS) has been widely used in driving simulators to study workload and fatigue, but not yet in racing-specific practice contexts. Here we present a pilot study using whole-head high-density fNIRS during simulated racing practice sessions with stable lap-time targets and no traffic. By synchronizing neural signals with telemetry, we demonstrate reproducible cortical responses associated with motor control and cognitive load, motivating the concept of neural “telemetry” for performance analysis and training.

Background

Functional near-infrared spectroscopy (fNIRS) is well suited for neuroergonomic research due to its tolerance of motion and ability to measure brain activity during naturalistic tasks. Prior studies have applied fNIRS extensively in driving simulators, including high-fidelity and motion-based environments, to study cognitive workload, fatigue, intention, and motion sickness [Balters2021, Zhang2020, Zhu2019]. These studies largely focus on safety-critical outcomes and error detection.

Competitive racing simulators, such as iRacing, represent a distinct operational regime. Rather than minimizing errors, drivers aim to achieve stable, repeatable performance near human sensorimotor limits while refining skill through practice. Racing practice sessions are highly structured, telemetry-rich, and repeated, making them an ideal but underexplored platform for neuroergonomic investigation of performance optimization, motor learning, and cognitive efficiency.

To date, no studies have examined whole-head cortical dynamics during simulated racing practice. Moreover, most prior simulator studies rely on sparse prefrontal fNIRS coverage, limiting insight into distributed motor, visual, and associative cortical contributions. High-density, whole-head fNIRS enables a more comprehensive characterization of brain activity during complex, continuous control tasks and supports emerging concepts of neural performance telemetry.

Methods

Neural and behavioral data were collected during simulated racing practice sessions using a commercial racing simulator (iRacing) with steering wheel and pedal controls. Participants completed repeated practice laps on a fixed track with no traffic, aiming for stable, consistent lap times while learning the course. Brain activity was measured using the wearable whole-head high-density ninjaNIRS fNIRS system, which provides coverage of frontal, motor, parietal, and visual cortices using 56 sources and 144 detectors [O’Brien2024] (Fig. 1a).

Vehicle telemetry, including steering wheel angle and lap timing, was synchronized with fNIRS data acquisition. Neural data were analyzed in channel space by estimating lap-evoked hemodynamic responses using a general linear model (GLM), with trial onset defined at the start of each lap (Fig. 1b). The GLM was applied to both oxygenated (HbO) and deoxygenated (HbR) hemoglobin time courses and included third-order polynomial drift regressors and a global mean short-separation regressor to reduce systemic physiological contributions. Evoked responses

were estimated over the full duration of each ~60 s lap and compared with steering wheel angle as a continuous indicator of position on the track.

In addition, lap-to-lap reproducibility of neural responses within practice sessions was assessed to quantify the stability and variability of cortical activation patterns across repeated laps. Pilot data are reported from two subjects; data collection from an additional ten subjects is ongoing and expected to be completed by the time of the conference.

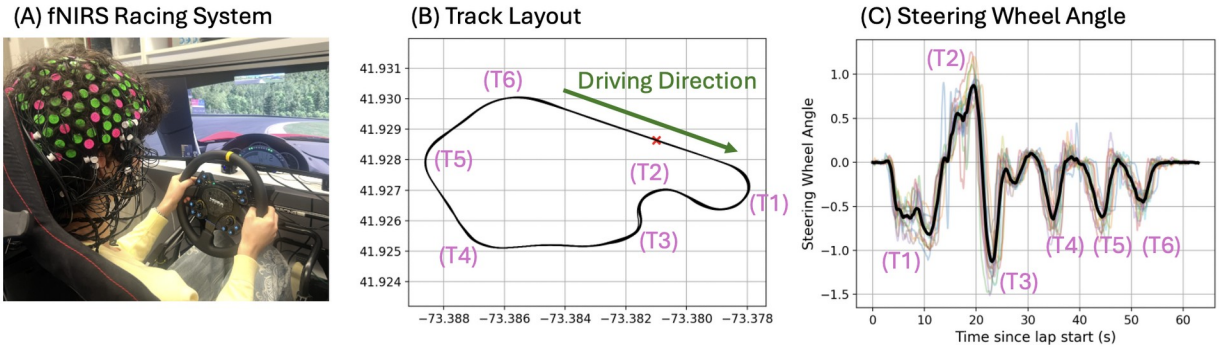

Fig 1. (A) A photograph of the whole head high density fNIRS system on the subject in the racing simulator. (B) A diagram of the car trajectory along the race track for several laps. The lap start is indicated by the red x. The 6 turns are also indicated. Coordinates are lattitude vs longitude. (C) Shows a sphaghetti plot of the steering wheel angle for several laps and the mean angle in black for 16 of 23 laps within 5 sec of the median lap time. Longer lap times result from track incidents that are presently excluded from analysis.

Results

Pilot data revealed robust, repeatable cortical hemodynamic evoked responses time-locked to execution of each lap. Strong hemodynamic responses were observed in medial prefrontal and motor brain regions (Fig. 2A & B), with response magnitude and temporal structure correlating with steering wheel angle, reflecting motor execution and associated cognitive load during turns. Visual cortex also showed consistent lap-locked responses, corresponding to the repeated visual flow of the track.

Across laps within a session, neural responses exhibited high lap-to-lap correlation, particularly in visual cortex (Fig. 2C). Correlations in prefrontal and motor regions were also present but systematically lower, indicating greater variability in attentional engagement and motor effort across laps despite stable visual input. This pattern is consistent with variable cognitive control and effort during skill refinement, contrasted with highly stereotyped visual stimulation.

These results demonstrate the feasibility of whole-head fNIRS during simulated racing practice and reveal structured, interpretable neural dynamics aligned with vehicle telemetry.

Discussion

This pilot study extends neuroergonomic fNIRS research into the domain of simulated racing practice, emphasizing performance stabilization and skill learning rather than error detection or safety. The use of whole-head high-density fNIRS enabled simultaneous observation of motor, prefrontal, and visual cortical dynamics during continuous control.

The observed lap-locked responses and their region-specific reproducibility suggest a framework for neural “telemetry” analogous to traditional vehicle telemetry. Visual cortical activity was highly stereotyped across laps, reflecting consistent sensory input, whereas greater variability in prefrontal and motor regions likely reflects fluctuations in cognitive load, control strategy, and motor refinement. We hypothesize that increased driving skill will be associated with reduced

prefrontal engagement and lower motor variability, reflecting increased automaticity or “muscle memory.”

Although current data are limited to practice sessions without traffic, this controlled setting provides a critical baseline for future studies incorporating competitive racing, traffic, and pressure. Ultimately, integrating neural metrics with conventional telemetry may support neurofeedback-guided training, enabling drivers to review not only lap times and inputs, but also the cognitive and neural efficiency underlying performance.

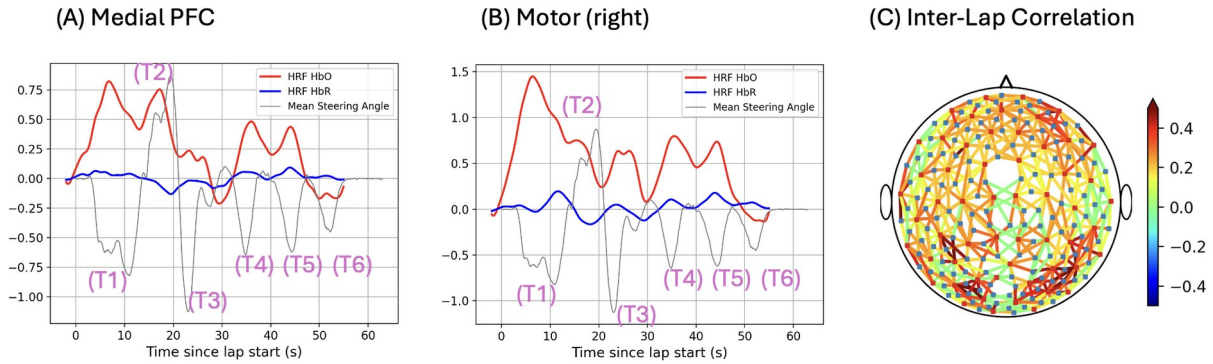

Fig. 2. fNIRS functional responses measured during 16 cleanly completed laps for one subject. (A) and (B) show the hemodynamic response measure in the medial PFC and right motor regions respectively. (C) Shows the significant mean inter-lap correlations of the HbO signal for the 120 pairs of laps.

Disclosures

The authors have no disclosures to report related to this work.

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