Brain in the Loop Learning Using Functional Near Infrared Spectroscopy

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Abstract. The role of practice is crucial in the skill acquisition process and for assessments of learning. In this study, we used a portable neuroimaging technique, functional near infrared (fNIR) spectroscopy for monitoring prefrontal cortex activation during learning of spatial navigation tasks throughout 11 days of training and testing. Two different tasks orders, blocked and random, were used to test the effect of the practice schedule on the acquisition and transfer of 3D computer mazes. Results indicated variable decreases in the hemodynamic response during the initial days of practice. Although there were no differences in mean oxygenation for the practice orders across acquisition the random practice order used less oxygenation than the blocked order for the more difficult tasks in the transfer phase Use of brain activation and behavioral measures provides can provide a more accurate depiction of the learning process. Since fNIR systems are safe, portable and record brain activation in ecologically valid settings, fNIR can contribute to future learning settings for assessment and personalization of the training regimen.

Keywords: Optical Brain Imaging, functional near infrared spectroscopy, fNIR, Learning, Spatial navigation, contextual interference.

1 Introduction

The advent of new and improved brain imaging tools, that allow monitoring brain activity in ecologically valid environments, is expected to allow better identification of neurophysiological markers of human performance and learning. Further, deployment of portable neuroimaging technologies to real time settings could help assess cognitive and motor task related brain activations for objective assessment of mental effort and cortical processing involved for the task at hand. Functional Near-Infrared Spectroscopy (fNIR) is an emerging optical brain imaging technology that relies on

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optical techniques to detect changes of hemodynamic responses within the prefrontal cortex in response to sensory, motor, or cognitive activation.

The role of practice is crucial in the skill acquisition process and for assessments of learning. By examining the cognitive and behavioral output during the performance and learning of selected cognitive and motor tasks, along with a detailed examination of the neural activity obtained from fNIR, it may be possible to gain insight into the impact of practice on learning, transfer and the skill acquisition processes. This paper discusses the neural mechanisms of learning and skill acquisition using fNIR with Maze Suite 3D spatial navigation tasks using a contextual interference paradigm.

The organization of practice when learning multiple tasks (e.g., [1, 2]) is a learning phenomenon called the contextual interference effect. The effects of contextual interference are evident when individuals acquire multiple tasks under different practice schedules. High contextual interference (random (RAN) practice order) is created when the tasks to be learned are presented in a non-sequential, unpredictable order. Low contextual interference (blocked (BLK) practice order) is created when the tasks to be learned are presented in a predictable order

The specific aim of this pilot study is to identify brain based biomarkers of learning and its relationship to task performance improvement with practice as measured by fNIR spectroscopy which is a safe, non-invasive, affordable and portable neuroimaging technology that can be used to monitor hemodynamic changes that occur in the brain, i.e., blood oxygenation and blood volume, during select cognitive tasks such as mental workload [3-6], task difficulty/problem solving [7-9], performance[10-12] and learning[12-14] assessment tasks. Moreover, fNIR data can be collected in quiet settings unlike functional magnetic resonance imaging (fMRI) that exposes subjects to noise and confines them to restricted spaces and a supine position during the data acquisition process. These qualities pose fNIR as an ideal methodology for monitoring cognitive activity-related hemodynamic changes not only in laboratory settings but also under ecologically valid conditions – real world environments.

For the experimental paradigm, fNIR measures were integrated into a virtual 3D navigation tasks generated with MazeSuite [15, 16] (Drexel University). The protocol involved execution of wayfinding tasks throughout 11 days. Two different groups, BLK and RAN practice orders were used for learning of mazes (virtual environments /labyrinths) during acquisition and more difficult (complex) mazes during retention. A 16-channel continuous wave (CW) fNIR system designed by the Optical Imaging Team at Drexel University (see [3]) was used to monitor the prefrontal cortex during task performance.

2 Methods

2.1 Participants

Eight right-handed participants (assigned using the Edinburgh Handedness Inventory[17]) volunteered for this study. Participants self-reported that they did not have any neurological or psychiatric history; that they were medication-free, and had normal or corrected-to-normal vision. Participants gave written informed consent for the study, which was approved by the Institutional Review Board at Drexel University, and were paid for their participation. Participants were randomly assigned to either a BLK practice order or RAN order.

2.2 Experiment Protocol

The spatial navigation tasks involved wayfinding in virtual 3D environments rendered using MazeSuite software [15, 16] developed in our lab. Figure 1 below displays a screen from a one of the 3D maze (labyrinths) that participants interacted with using keyboard and mouse controls. The first day of the experiment involved familiarization with the task controls and generic navigation in an orientation maze. Tasks for the acquisition period (3 mazes) were performed on each day 2 through day10. On day 11, transfer tasks (2 novel mazes) were executed. For the BLK group, one type of maze was practiced on each day with three days of practice per maze. For the RAN group, all mazes were practices on all days. Total of mazes for all subjects were same (acquisition: 9 days x 15 repetitions per day + transfer: 1 day x 12 repetitions per day). Transfer practice order was the same as the acquisition order with the BLK group having the transfer mazes in a blocked order while the RAN group had the transfer mazes in a random order. The transfer mazes were used to determine the extent to which each subject was able to generalize their learning and practice with acquisition mazes – given that robust learning assessments are best illustrated through generalizability tests like transfer.

Fig. 1. Functional Near Infrared Spectroscopy sensor (head band) covers forehead of participants (left) and screen shot from a maze rendering on computer screen (right).

2.3 fNIR Data Acquisition

The continuous wave fNIR system (fNIR Devices LLC; www.fnirdevices.com) used in this study is connected to a flexible sensor pad that contains 4 light sources with built in peak wavelengths at 730 nm and 850 nm and 10 detectors designed to sample cortical areas underlying the forehead. With a fixed source-detector separation of 2.5 cm, this configuration generates a total of 16 measurement locations (optodes) [3, 18]. For data acquisition and visualization, COBI Studio software [15] (Drexel University) was used. The sampling rate of the system was 2Hz. During the task, a serial cable

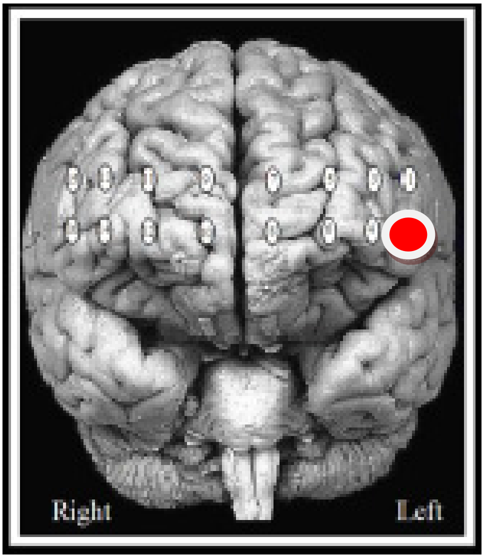

Fig. 2. Measurement locations of the 16 optodes [18]. The location of optode #2 (indicated by the red circle) is close to AF7 in the International 10–20 System and is located within the left prefrontal cortex (inferior frontal gyrus).

between the fNIR data acquisition computer and MazeSuite presentation computer was used to transfer time synchronization signals (markers) that indicate the start of sessions and onset of maze tasks.

2.4 Data Analysis

For each participant, raw fNIR data was low-pass filtered with a finite impulse response, linear phase filter with order of 20 and cut-off frequency of 0.1Hz to attenuate the high frequency noise [3]. Motion artifact contaminated sessions and saturated channels (if any), in which light intensity at the detector was higher than the analog-to-digital converter limit were excluded [19]. Using time synchronization markers, fNIR data segments for rest periods (15 seconds rest period between trials) and task periods (maze task performance) were extracted. Blood oxygenation changes within dorsolateral prefrontal cortex for all optodes were calculated using the Modified Beer Lambert Law (MBLL) for task periods with respect to rest periods at beginning of each task[3]. Dependent measures included relative changes in the mean oxygenation change for optode #2 (see Fig 2) and behavioral measure of path length for the mazes For acquisition for optode #2 mean oxygenation and mean path length, 2 X 9 (Practice Order X Day) mixed model ANOVAs with repeated measures on the last factor. In this repeated measures design, participants were considered a random-effects factor, whereas Practice Order was considered a fixed-effect factor. To test a fixed-effect with one random effect in the model, the appropriate denominator term for the

F-statistic was determined by limiting the error term for the interaction of the fixed and random factors to zero [20]. For transfer, planned contrasts of the BLK vs RAN practice orders were calculated for optode #2 mean oxygenation changes and mean path length. The significance criterion for all tests was set at $\alpha = 0.05$.

2.5 Behavioral Measures

For acquisition, the behavioral measure mean path length (arbitrary units (a.u.), had a significant interaction of Practice Order by Day with [$F_{(8,920)} = 7.43$, $p < 0.001$] and significant main effect of Day [$F_{(8,920)} = 22.82$, $p < 0.001$]. The main effect of Practice Order was not significant [$F_{(1,920)} = 3.14$, $p = 0.137$]. The change of average path length for the BLK and RAN groups across acquisition and transfer is depicted in Fig. 3. The planned contrast resulted in no significant difference between the BLK and RAN practice orders in the transfer phase with [$F_{(1,94)} = < 1.0$, $p = 0.591$].

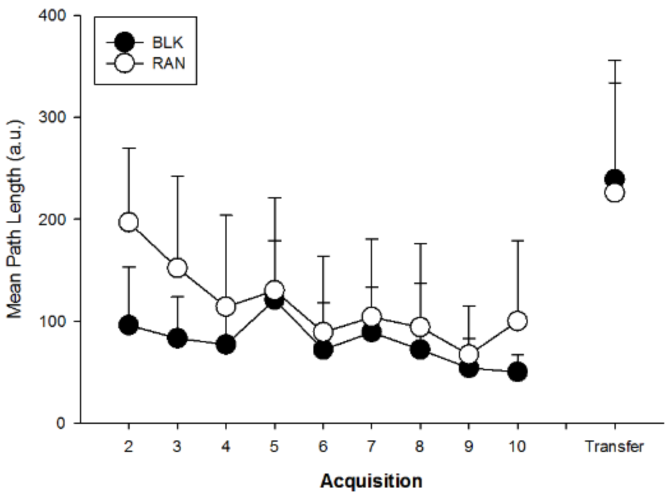

Fig. 3. Average navigation path length for all subjects during acquisition and transfer for blocked order group (BLK) and random order group (RAN). Error bars are standard deviations (SD)

2.6 fNIR Measures

In this paper, the left inferior frontal gyrus (location of optode #2 – see Fig. 2) mean oxygenation change (µmolar) values were assessed for all maze trials across the acquisition phase (9days) and for the transfer phase (day 11) transfer. Both the interaction of Practice Order X Days [$F_{(8,991)} = 2.03$, p=0.04], and the main effect of Days [$F_{(8,991)} = 2.00$, p =0.043] were significant for acquisition. There was no significant main effect of Practice Order with [$F_{(1, 991)} = < 1.0$, p =0807]. For transfer, the planned contrasts yielded a significant difference with [$F_{(1,84)} = 6.86$, p =0.01]. Depicted in

Fig.4 are the mean oxygenation changes for practice orders plotted as a function of the acquisition and transfer phases. More difficult tasks were performed during transfer and the change in oxygenation values was higher for the BLK practice order relative to the end of acquisition. However, oxygenation for the RAN practice order was lower compared to the BLK practice order during transfer and the RAN practice order had lower mean oxygenation during transfer relative to the end of acquisition.

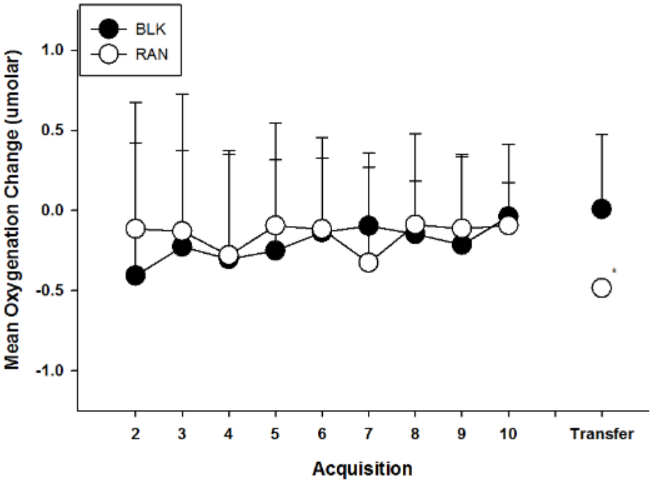

Fig. 4. Average oxygenation changes at optode #2 across acquisition and transfer stages. Error bars are standard deviations (SD). * ($p < 0.05$).

3 Discussion

The purpose of this study was to test the practice order effect with spatial navigation tasks. Behavioral performance measures and cortical hemodynamic responses as measured by wearable optical brain imaging were collected to compare changes across 11 days of practice and for two practice orders: BLK and RAN. Our results indicate differential patterns for behavioral and fNIR measures for the different practice orders.

During acquisition phase (day2-10), navigation path length (behavioral measure) improved across both practice orders for the acquisition phase (Fig. 3). This expected results showed that participants improved their navigation skill with more practice. The mean path length traveled was lower for BLK order across the days of the acquisition period compared to the RAN practice order. The oxygenation (fNIR measure) was variable throughout the acquisition phase for both practice orders (Fig. 4). There was a quicker reduction in oxygenation for the BLK practice order relative to the RAN order and both BLK and RAN orders had similar oxygenation values at the end of acquisition.

During the transfer phase (day11), more complex maze tasks were presented. Average navigation path length for RAN group was higher compared to BLK group, suggesting that RAN practice order prepared the participants for the more complex task. Similarly, oxygenation during the transfer phase was lower for the RAN group compared the BLK group suggesting that RAN group used less mental effort to complete the task compared to the BLK order group. These findings corroborate the PET findings with spatial navigation of virtual mazes reported by Van Horn and colleagues [21]. In addition, using fMRI, Wymbs and Grafton [22] reported that the left inferior frontal gyrus was differentially activated during late learning as a function of practice schedule for the sequence execution of a go/no-go task. Our transfer findings illustrate that there is a differential relative mean oxygenation of the left inferior frontal gyrus region for RAN and BLK practice orders for spatial navigation tasks. These results help to extend our understanding of the contextual interference effect regarding the influences of the practice order and task type on neural function [21-26].

This study tested the effects of learning spatial navigation tasks in virtual environments. Results indicated that behavioral performance and oxygenation in the anterior prefrontal cortex is sensitive to both the amount of practice and the order of practice in learning multiple tasks. This study provides preliminary information about fNIR measures of the anterior prefrontal cortex hemodynamic response and its relationship to learning/skill acquisition. Since fNIR technology allows the development of mobile, non-intrusive and miniaturized devices, it has the potential to be used in future learning/training environments to provide objective, task related brain-based measures for optimizing the learning process.

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