Brain-in-the-Loop Learning Using fNIR and Simulated Virtual Reality Surgical Tasks: Hemodynamic and Behavioral Effects

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Abstract. Functional near infrared spectroscopy (fNIR) is a noninvasive, portable optical imaging tool to monitor changes in hemodynamic responses (i.e., oxygenated hemoglobin (HbO)) within the prefrontal cortex (PFC) in response to sensory, motor or cognitive activation. We used fNIR for monitoring PFC activation during learning of simulated laparoscopic surgical tasks throughout 4 days of training and testing. Blocked (BLK) and random (RND) practice orders were used to test the practice schedule effect on behavioral, hemodynamic responses and relative neural efficiency ($EFF_{rel\text{-}neural}$) measures during transfer. Left and right PFC for both tasks showed significant differences with RND using less HbO than BLK. Cognitive workload showed RND exhibiting high $EFF_{rel\text{-}neural}$ across the PFC for the *coordination* task while the more difficult *cholecystectomy* task showed $EFF_{rel\text{-}neural}$ differences only in the left PFC. Use of brain activation, behavioral and $EFF_{rel\text{-}neural}$ measures can provide a more accurate depiction of the generalization or transfer of learning.

Keywords: Cognitive effort and learning · fNIR · Simulation · Virtual reality · Transfer · Brain sensors and measures · Contextual interference

1 Introduction

Functional near infrared spectroscopy (fNIR) is a noninvasive, emergent optical imaging tool to monitor changes in hemodynamic responses (i.e., oxygenated hemoglobin (HbO)) within the prefrontal cortex (PFC) in response to sensory, motor or cognitive activation [1–6]. The PFC serves as the highest cortical area responsible for motor planning, organization and regulation and it plays an important role in the

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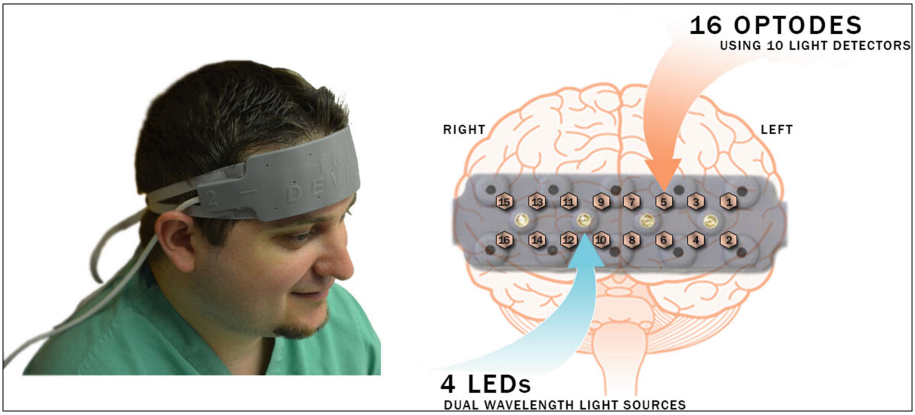


Fig. 1. Functional near infrared spectroscopy sensor (head band) covers forehead of participants (left) and sensor overlaid on brain image with sensor configuration of light sources, detectors and optodes (right).

integration of sensory and mnemonic information, the regulation of cognitive function and action, and works with other cortical circuits with executive functions including working memory [7]. fNIR (Fig. 1) is a portable brain imaging tool for the identification of neurophysiological markers of human learning and performance [4–6]. It can monitor brain activity in both ecologically valid environments (i.e., surgical suites, classrooms, offices) or in the laboratory. The use of portable, safe and accessible neuroimaging technologies, i.e., fNIR, allows for data collection to occur in real time settings thereby permitting the simultaneous testing of cognitive and motor task related brain activations along with behavioral performance metrics [4–6]. These hemodynamic brain activation biomarkers could lead to the development of training and assessment protocols that incorporate cognitive workload (i.e., mental effort via cortical processing) and behavioral performance measures for assessments of task and goal attainment [4].

Cognitive Load Theory (CLT) focuses on designing instructional methods and exemplars that enhance cognitive processing and facilitate the application of acquired skills and knowledge to novel situations or skills [8–10]. Paas and colleagues [8] differentiated between cognitive load, mental load and mental effort regarding CLT with *cognitive load* representing multiple dimensions associated with the burden a performed task imposes on a learner's cognitive system. *Mental load* is the section of cognitive load that reflects task demands interacting with learner characteristics (i.e., expertise level, abilities) while *mental effort* concerns the demands placed on the cognitive capacity to perform the task [8]. Paas [8] discussed the applications of relative instructional efficiency to different contexts along with the use of self-report measures of effort [9, 10] and some physiological measures (i.e., heart rate variability and eye movement tracking). However, no one has explicitly applied and assessed objective neural measures of cognitive effort with exception of Ayaz et al.'s work with Unmanned Aerial Vehicles [e.g., 22].

Surgical training has evolved from the Halstedian apprenticeship model of 'see one, do one, teach one' towards an outcomes-based educational paradigm requiring achievement of core competencies [11]. This paradigm shift is the result of a cumulative effect of limited resident work hours, concerns for patient safety, ethical concerns for learning new procedures on patients and the cost of resident training in the operating room [12]. Simulation has become an integral part of surgical skills training and the Accrediting Committee for Graduate Medical Education (ACGME) now requires surgical residency programs to include simulation and skills laboratories to address the acquisition and maintenance of surgical skills [13, 14]. Several studies identified the benefit of increased skill acquisition with simulation training. Stefanidis noted that skills acquired on simulators have repeatedly and consistently demonstrated positive transfer to the operating room, and proficiency-based training maximizes these benefits [15]. The use of a standardized, simulation-based curriculum (e.g. Fundamentals of Laparoscopic Surgery (FLS)) is mandated for surgical training programs in the United States. While there are a myriad of studies establishing the efficacy of simulation in teaching operative skill, there is no consensus on the ideal practice model for the most efficient method of acquiring these skills. The use of educational and movement science theories in the development of curricula for teaching surgical skills is a relatively new concept in the surgical literature; as well the use of neurophysiological markers in the evaluation of skill acquisition is equally novel.

Practice organization when acquiring multiple tasks is a learning phenomenon called the contextual interference effect, which incorporates, blocked (BLK) and random (RND) practice schedules into the specific order the learner will perform the tasks during the acquisition phase [16–18]. Low contextual interference (BLK practice) is created when the tasks to be learned are presented in a predictable order while high contextual interference (RND practice) occurs when the tasks to be learned are presented in a non-sequential, unpredictable order. Laparoscopic training curricula utilize BLK orders where trainees perform the same task for a fixed number of times, or until a predefined proficiency level is achieved, before being allowed to move to the next task in the curriculum [19]. Given the natural training environment of surgical skill curricula combined with the importance of patient safety and high performance accuracy under stress (i.e., cognitive workload), we conducted an experiment to test brain measures of cortical activation, selected behavioral performance metrics and cognitive workload when five different surgical laparoscopy simulation tasks were acquired with different practice schedules. The specific aim of this pilot study is to identify brain based biomarkers of neural activity and cognitive workload of transfer of learning using simulated laparoscopic surgical tasks performed in a virtual environment.

2 Methods

2.1 Participants and Experimental Protocol

Fifteen medical students between the ages 24 to 28 years volunteered for the study. Three were rejected due to technical issues during recording and missing sessions and another was rejected during transfer for poor data quality on the majority of the optodes. Eleven medical students with no previous exposure to laparoscopic surgery were randomly assigned to either a BLK (n = 2_F; n = 3 $_M$) or RND (n = 2_F; n = 4 $_M$) practice order using a virtual reality (VR) laparoscopic simulator (LAPSIM®). The medical students provided written informed consent for participation in the study via a Drexel University Institutional Review Board approved protocol. All participants were medication-free, with normal or corrected-to-normal vision.

Each student performed 36 acquisition trials each of three VR laparoscopic tasks (i.e., *camera navigation*, *grasping* and *fine dissection*) across three days and approximately 72 h following acquisition, 6 retention (2 each of the acquisition tasks) and 6 transfer trials ("*coordination*" – involved *camera navigation* and *grasping* tasks; "*cholecystectomy*" - dissection, application of clips and cutting vessels using scissors). PFC activity was monitored during all phases for 16 optode sites using fNIR.

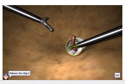
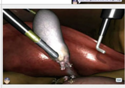
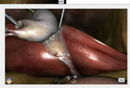
2.2 Simulation Tasks

A total of five tasks from the LapSim 2013 Simulator (www.surgical-science.com) were used in this study (See Table 1 for an image and description of each task). These tasks represented the basic laparoscopy skills a surgeon would perform during an operation (*Camera Navigation*, *Lifting and Grasping* and *Fine Dissection*), and also serve as a comprehensive basis for the participant to complete the two transfer tasks, *Coordination* and *Cholecystectomy* (removal of the gallbladder), on day 4 of the experiment.

2.3 Data Collection

The optical brain imaging data was recorded using a continuous wave fNIR system (fNIR Devices LLC; www.fnirdevices.com) that has a flexible wearable sensor pad,

Table 1. Descriptions and images of the laparoscopic tasks from LAPSIM®

Task	Skill	Image	Objective
1	Camera Navigation		Practice handling a laparoscopic camera
2	Lifting and Grasping		Practice grasping, positioning, and orienting an object using a grasper (instruments as directed): right (green) and left (red)
3	Fine Dissection		Practice how to safely remove surrounding pieces of tissue from a vessel structure
4	Coordination		Practice handling an instrument and a camera simultaneously
5	Cholecystectomy	 	To learn how to dissect and remove the gallbladder from the liver bed with the diathermy hook while also stopping any resulting bleeding

hardware control box and data collection computer. The sensor houses 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 and a rectangular grid layout, sensor samples from 16 measurement locations (optodes) were collected and assessed (see Fig. 1) [4, 18]. For data acquisition and visualization, COBI Studio software [18] (Drexel University) was used on the data collection laptop with the sampling rate of the system was 2 Hz. During the task, the start and end of each session and simulation task were marked on the fNIR computer for time synchronization during post-processing [20].

2.4 Signal Processing

Raw light intensity signals were first visually inspected to reject problematic optodes such as over hairlines or bad optical coupling. To reject portions of the data with motion artifact contamination, an automated sliding window motion artifact (SMAR) algorithm [21] that uses a coefficient of variation-based approach was adopted. To eliminate the high frequency noise and physiological artifacts, such as heart rate and respiration rate, a low-pass finite impulse response filter of cut-off frequency 0.1 Hz and a 20th order was applied to raw light intensity data.

Hemodynamic changes (ΔHbO) within the anterior PFC for all optodes were calculated using the Modified Beer Lambert Law [4]. The data epochs for each surgery simulation trial were then extracted using time synchronization markers and they were baseline corrected with respect to the start of the trial.

2.5 Relative Neural Efficiency Analyses

A multidimensional computational approach was used to simultaneously evaluate behavioral performance and a neural measure of cognitive effort during performance using the framework set forth by Paas and van Merriënboer [9] in which they assessed relative efficiency of performance and self-reported mental effort. We are using an objective measure of cognitive effort (i.e., ΔHbO), which is obtained from each participant during performance of each trial. Our computational approach uses the 2D model of Paas [8, 9], where the global score (performance) and ΔHbO (cognitive effort) are standardized into z-scores for each transfer task.

$$P_z = \frac{G_{\mathrm{i}} - G_{\mathrm{GM}}}{G_{SD}} \qquad CE_z = \frac{\Delta HbO_{\mathrm{i}} - \Delta HbO_{\mathrm{GM}}}{\Delta HbO_{SD}}. \tag{1}$$

Where P_z is the standardized performance score in standard deviation units,

G_i is the Global Score for each subject for each trial for each transfer task. G_{GM} is the grand mean Global Score for each transfer task and G_{SD} is the overall standard deviation for each transfer task. CE_z is the standardized cognitive effort in standard deviation units, HbO_i is the ΔHbO for each subject, trial, transfer task and left or right PFC, ΔHbO_{GM} is the grand mean for the ΔHbO for each transfer task and left or right

PFC while ΔHbO_{SD} is the overall standard deviation for each transfer task and left or right PFC.

This equation is based on calculating the perpendicular distance of a point (CE_z, P_z) defined by the cognitive effort and performance for each practice schedule for each transfer task on the CE_z - P_z axis to a zero relative neural efficiency line (EFF = 0) where $CE_z = P_z$. Given the line is $P_z - CE_z = 0$, to determine the distance from the zero relative neural efficiency line (E = 0) to the point with coordinates (e.g., $CE_{z\ -RA\text{-}Coordination\text{-}\ LPFC}$, $P_{z\ -RA\text{-}Coordination}$), the equation for the distance for the relative neural efficiency score, $EFF_{rel\text{-}neural}$ is then computed for each participant:

$$EFF_{rel-neural} = \frac{\mathrm{P_z} - \mathrm{CE_z}(2)}{\sqrt{2}} \tag{2}$$

.

2.6 Data Analysis

Dependent measures included relative changes in mean ΔHbO and $\mathrm{EFF}_{\text{rel-neural}}$ for the left and right PFCs; and a behavioral performance metric of a global score (percentage reflecting the time, instrument path length and accuracy of performance of the task) during transfer for the *coordination* and *cholecystectomy* surgical VR tasks. We assessed if the data met the assumptions of normality and homogeneity of variance for all dependent measures. Non-parametric randomization tests with 10,000 Monte Carlo samples were used to determine if there were differences between BLK vs RND practice orders for each task separately. If the data were non-normally distributed, we used a Mann-Whitney U non-parametric test. Effect sizes were calculated and used to aid in interpretation of the data. The significance criterion for all tests was set at $\alpha = 0.05$. Number Cruncher Statistical Software (NCSS; www.ncss.com) was used for the analyses.

3 Results

We hypothesized that during transfer there will be higher relative neural efficiency, higher behavioral performance metrics, and lower HbO hemodynamic responses with RND practice compared to BLK. For the *coordination* and *cholecystectomy* VR tasks, the behavioral, ΔHbO and $\mathrm{Eff}_{\text{rel-neural}}$ measures descriptive statistics, confidence intervals and effect sizes are reported in Table 2.

3.1 Behavioral Results

For both tasks, the behavioral measure descriptive statistics, confidence intervals and effect sizes are reported in Table 2. The *coordination* task Global Score (%) approached significance [$t_{(31)} = -1.89$, $p = 0.068$] with RND averaging better than the passing score (80 %) relative to BLK. For the *cholecystectomy* task, there were no practice schedule differences for the Global Score (%) [$t_{(31)} = 0.237$, $p = 0.827$] .

Table 2. Descriptive statistics of the *coordination* and *cholecystectomy* simulated laparoscopic virtual reality (VR) transfer tasks for changes in hemodynamics (oxygenated hemoglobin (ΔHbO) (μm), behavioral (global scores (%)) and relative neural efficiency (Effrel-neural) measures across practice schedules.

Coordination VR Task						
Dependent Variable	**Practice Schedule**	**Mean**	**± SD**	**CI[1] (LL**	**UL)**	**ES[2]**
Global Score (%)	BLK	77.333	12.585	70.341	84.302	0.73
	RND	84.944	10.563	79.693	90.202	
ΔHbO (left)	BLK	0.235	1.320	-0.495	0.966	1.31
	RND	-1.578	1.680	-2.129,	-1.027	
ΔHbO (right)	BLK	0.610	0.945	0.087	1.134	2.55
	RND	-1.391	0.802	-1.790	-0.992	
$Eff_{rel\text{-}neural}$ (left)	BLK	-0.686	0.701	-1.074	-0.292	-1.86
	RND	0.571	0.785	0.181	0.962	
$Eff_{rel\text{-}neural}$ (right)	BLK	-0.802	0.719	-1.201	-0.404	-2.04
	RND	0.669	0.855	0.244	1.094	

Cholecystectomy VR Task						
Dependent Variable	**Practice Schedule**	**Mean**	**± SD**	**CI[1] (LL**	**UL)**	**ES[2]**
Global Score (%)	BLK	76.600	14.272	68.702	84.504	0.09
	RND	74.944	23.740	63.141	86.750	
ΔHbO (left)	BLK	1.178	1.820	0.776	2.726	0.79
	RND	-0.061	1.671	-0.920	0.798	
ΔHbO (right)	BLK	1.198	2.234	0.751	3.225	0.61
	RND	0.127	1.700	-0.747	1.001	
$Eff_{rel\text{-}neural}$ (left)	BLK	-0.313	0.954	-0.841	0.215	-0.59
	RND	0.276	1.199	-0.320	0.873	
$Eff_{rel\text{-}neural}$ (right)	BLK	-0.292	0.977	-0.834	0.249	-0.55
	RND	0.266	1.211	-0.357	0.888	

KEY: BLK- Blocked; RND-Random; ΔHbO – change in mean oxygenated hemoglobin (μmolar); $Eff_{rel\text{-}neural}$ -relative neural efficiency. [1] Confidence Intervals (95%) with the lower limit (LL) and upper limit (UL) for each practice schedule and variable. [2]Effect sizes (ES) reflects RND-BLK differences/pooled SD. A positive value indicates an advantage for RND for the Global Score and ΔHbO while positive values for the relative neural efficiency measures ($Effrel_{\text{-}neural}$) indicate a disadvantage for RND relative to BLK.

3.2 fNIR Measures

In this paper, the optodes of the PFC are averaged across the left (average of optodes #1-#8) and right (average of optodes #9-#16 – see Fig. #1) regions with mean (μmolar) values assessed for all transfer trials for the *coordination* and *cholecystectomy* tasks. The mean ΔHbO was significant for both the left and right PFCs [$t_{(31)} = 4.29$, $p < 0.001$ and $t_{(31)} = 6.98$, $p < 0.001$] for the *coordination* VR task with RND having substantially lower HbO values than BLK. In addition, for the *cholecystectomy* VR task, there were significant differences between the RND and BLK practice orders for both the left and right PFCs [$t_{(31)} = 2.88$, $p = 0.007$ and $t_{(30)} = 2.67$, $p = 0.012$], respectively.

Depicted in Fig. 2 are the mean ΔHbO differences for BLK-RND plotted as a function of the two tasks for the left and right PFCs. During transfer of the *coordination* task, RND practice exhibited large effects (see Table 2) and lower means HbO values than BLK practice for the left and right PFCs. For the more difficult *cholecystectomy* task RND and BLK practice differences were detected however the magnitude of the differences were smaller.

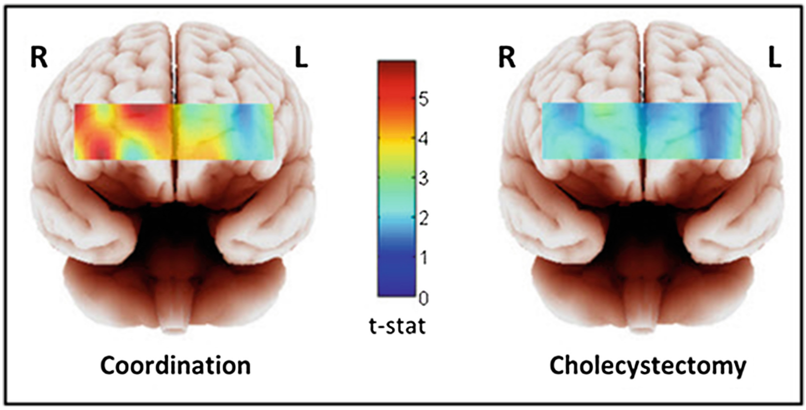


Fig. 2. Topographical map [20] of contrast t-tests ($t_{(25)} \leq 2.206$, $p \leq 0.05$, 2-tailed) of the mean change in oxygenated hemoglobin (μmolar) for the *coordination* and *cholecystectomy* tasks. Contrasts represent average blocked (BLK) – random (RND) differences.

3.3 Cognitive Workload: Relative Neural Efficiency Analyses

The mean $EFF_{rel\text{-}neural}$ was significant for both the left and right PFCs [$t_{(31)} = 4.81$, $p < 0.001$ and $t_{(31)} = -5.28$, $p < 0.001$] for the *coordination* VR task with RND having very large effects and high relative neural efficiency compared to the low relative neural efficiency for the BLK practice order (see Table 2). In addition, for the *cholecystectomy* VR task, there were significant differences between the RND and BLK practice orders for the left PFC [$Z = -1.97$, $p = 0.049$] while the right PFC was just below significance [$Z = -1.95$, $p = 0.054$].

In the relative neural efficiency graphs, the fourth quadrant represents low efficiency, where low performance is achieved with high cognitive effort. The second quadrant represents high efficiency where high performance is attained with low cognitive effort. The diagonal $y = x$ is the neutral axis, where relative neural efficiency ($Eff_{rel\text{-}neural} = 0$) representing equal cognitive effort and performance. To determine if there are significant differences in $Eff_{rel\text{-}neural}$, we tested the Euclidian distance differences between practice schedules for each transfer task within each PFC. The $EFF_{rel\text{-}neural}$ for each task and practice schedule within each PFC are depicted in Fig. 3.

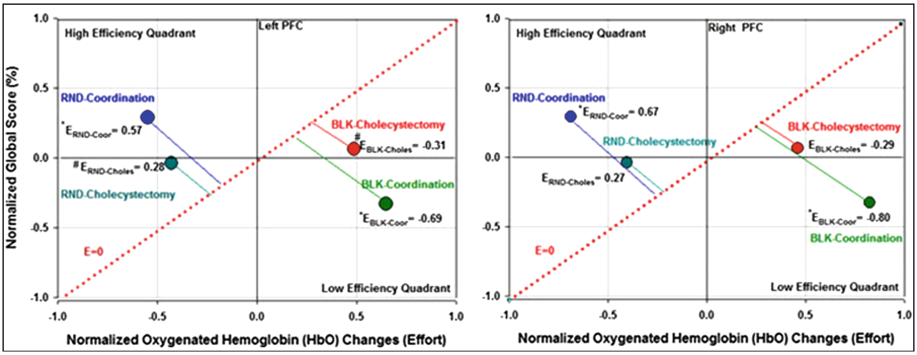


Fig. 3. Cognitive workload (effort) relative neural efficiency graph with normalized global scores (%) representing performance vs. normalized change in oxygenated hemoglobin (Effort) for blocked (BLK) and random (RND) practice schedules with the *coordination* and *cholecystectomy* tasks. the second quadrant represents high relative neural efficiency and fourth quadrant indicates low relative neural efficiency area. y = x is where relative neural efficiency (E) is zero. *($p < 0.001$), # ($p < 0.05$).

4 Discussion

Our results indicate differential patterns for the behavioral, fNIR and relative neural efficiency cognitive workload measures for the distinctive practice orders and tasks. Although there were no practice schedule differences for the behavioral performance measure, Global Score, we did detect differences between the BLK and RND practice schedules for the relative neural efficiency, i.e., cognitive workload, metric. Specifically, in the *coordination* VR surgical task, for the left and right PFCs, RND had higher relative neural efficiency, which means that the learners performed the task with less cognitive load (minimum effort) and with a better performance score (maximum performance) than those learners who acquired the tasks in a BLK practice order (Fig. 3). For the *cholecystectomy* VR surgical task, RND practice had high relative neural efficiency relative to the BLK practice only in the left PFC. These results assist us in understanding the process of learning as mediated by task difficulty, behavioral performance and neurophysiological measures. The *coordination* VR task (see Table 1) can be thought of as a task that represents **interpolation** of the tasks and subtasks that were acquired during acquisition while the *cholecystectomy* VR task represents **extrapolation** of the acquisition tasks and subtasks. Acquiring tasks (*camera navigation*, *grasp and lift*, *fine dissection* – see Table 1) under a RND practice order facilitated the same cognitive and behavioral processes that were needed to perform the *coordination* and *cholecystectomy* tasks in transfer, which resulted in higher performance and lower cognitive effort relative to the BLK practice order. Our findings support our hypothesis that RND practice facilitates generalization by better performance and lower neural demands (i.e., cognitive effort) during transfer of simulated laparoscopic surgical tasks.

Our results provide preliminary information about fNIR measures of the anterior PFC hemodynamic response and its relationship to generalizations of skill learning or transfer of surgical laparoscopic tasks in a VR environment. These findings are comparable to those noted by Shewokis and colleagues [5, 18, 26] using fNIR and 3-D spatial navigation tasks and 3-D UAV piloting tasks [22]. In addition, using fMRI, Wymbs and Grafton [23] 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. Shewokis et al. [26] showed transfer results illustrating that there is a differential relative mean oxygenation of the left inferior frontal gyrus region (optode #2) for RND 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 [5, 17, 18, 23–26].

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 assessing cognitive workload and neural processing efficiency via different tasks, practice and feedback variables and allow for optimization of the learning process [27]. More importantly, we can observe the impact of positive transfer for tasks (i.e., *coordination* and *cholecystectomy* VR laparoscopy tasks) which illustrate the how learners integrate the processes they used as they learned multiple skills in a novel environment. Our findings support Stephanidis [15] and set the stage for additional learning scenarios within surgery training and medical education [12].

Incorporating brain-in-the loop learning during practice and testing assessments can lead to developing highly efficient and targeted learning/training programs that can adapt based on the learners' state. Preliminary results indicate that fNIR can be used to capture practice effects on performers. Moreover, given fNIR's qualities of portability and safety, this optical imaging modality is well suited for constructing learning assessments and protocols that meet the demands of 21st century learning environments (e.g., simulators, VR, online models, brain computer interfaces and so forth).

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