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SHORT COMMUNICATION

Hand motor learning in a musical context and prefrontal cortex hemodynamic response: a functional near-infrared spectroscopy (fNIRS) study

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Abstract

Due to movement automatization, the engagement of high-order cognitive processing during the motor execution of a task is expected to decrease over repetitions and practice. In this study, we assessed single session changes in the prefrontal hemodynamic signals in response to training a piano chord progression in an ecological experimental setting. We acquired functional near-infrared spectroscopy signals from 15 subjects without any previous experience on playing keyboard instruments. Our findings were that oxygenated hemoglobin changes at orbitofrontal cortex followed an inverted *U*-shaped curve over task execution, while the subjects' performance presented a steady slope. These results suggest an initial executive function engagement followed by facilitation of motor execution over time.

Keywords fNIRS · Learning · Cognitive control · Piano · Motor execution · Prefrontal cortex · Hemodynamics

Introduction

It is established that motor skills become less dependent on declarative cognitive functions with practice and repetition (Poldrack et al. 2005). As cognitive resources are limited (Wickens 2008), automatic motor skills are desirable to produce a smaller cognitive load [i.e., the mental workload necessary for motor control (Ono et al. 2015)], thus allowing cognitive resources to be allocated to other tasks.

Current literature proposed models for the mechanism behind motor skill acquisition (Eversheim and Bock 2001) and compared the performance of individuals on a dual-task paradigm, i.e., in the presence and absence of a parallel task (Beilock et al. 2002). These models and findings suggest that motor skill acquisition occurs in two distinct phases: the declarative and the procedural stage. During the declarative stage, there is a high cognitive load due to demanding of attention, decision making and motor planning to perform the task. On the other hand, the procedural phase is more fluent and less dependent on cognitive control (Gupta et al. 2012). This procedure of shifting the processing skill from a declarative to a procedural stage is called automaticity (Anderson 1982).

Recently, the improvements in neuroimaging techniques enabled researchers to go beyond the investigation based solely on behavior and performance while allowing the assessment of brain changes when learning a new skill. Wu et al. (2004) used functional magnetic resonance imaging (fMRI) to compare brain activation before and after a specific motor training. They found that the prefrontal cortex (PFC), among other regions, was less active after automaticity, thus supporting the declarative-procedural stage theory. The PFC is involved in executive processes essential for higher-order cognitive functions (Smith and Jonides 1999), which are necessary for the declarative stage of skill acquisition. Therefore, this region is a promising target to be investigated with neuroimaging tools during motor skill learning.

Among the functional imaging techniques currently available, there is a promising modality named functional near-infrared spectroscopy (fNIRS), which has been reported as

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a reliable tool to assess cognitive load and state (Fishburn et al. 2014). fNIRS is a safe and noninvasive imaging technique able to detect hemodynamic response changes related to local activation, based on the absorption and scattering of near-infrared light (Villringer 1997). In comparison with other imaging techniques, fNIRS is relatively robust to head motion, muscular artifacts, eye blinking, speech as well as environmental electrical noise (Balardin et al. 2017a, b; de Lima-Pardini et al. 2017). These features make it a promising tool in more ecological experiments, such as using a playing the piano or typing in the keyboard (Solovey et al. 2009). As a result, this technique is currently being used in human–computer interface settings to measure real-time cognitive states (Yuksel et al. 2015) and to optimize learning of piano skills (Yuksel et al. 2016).

Despite the potential of fNIRS to be employed in ecological settings, the number of fNIRS studies analyzing the acquisition of motor skills is scarce (Leff et al. 2011). We attempt to fill in this gap, by presenting an fNIRS-based method to investigate motor skill acquisition in PFC. With the assumption that automaticity reduces the demand for cognitive control during motor execution, we hypothesize that the PFC activation should decrease over repeated blocks of practice during the learning process. We chose a musical task (chord arpeggios) as this was suggested to be a useful framework to study brain plasticity (Wan and Schlaug 2010). Therefore, the goal of the present article is to investigate the temporal changes in prefrontal cortex hemodynamic response during a single session of practice.

Materials and methods

Participants

Fifteen right-handed participants (10 men, mean age of 21.5 years old, standard deviation of 2.4) took part in a cross-sectional study. In order to have a more homogeneous sample and to guarantee that the task difficulty was similar to all participants, none of them had previous experience playing piano or any other keyboard instrument (e.g., harpsichord, organ, etc.).

The UFABC Research Ethics Committee approved this study. All subjects read and signed a term of consent for voluntary participation in this study. According to federal rules, there was no compensation for taking part in this research. Before the experiment, we instructed the participants about the fNIRS and the task they would perform in a piano keyboard.

Task

The task consisted of learning how to play a simple sequence of notes on a piano keyboard in a block experimental design. During the task blocks, the subjects had 30 s to practice three arpeggiated chords (*C* major, *A* minor and *F* major) following this sequence in each of the blocks. Each chord had four notes (its fundamental, the third, the fifth and the octave above the fundamental). They were instructed to use their left hand to play each note while using all their fingers but the fourth (ring) finger. The same notes were exhibited on the monitor during each of the ten blocks. After each block, the volunteers marked on a visual analog scale the subjective difficulty of the corresponding task block. It was followed by 22 s resting block, in which they were instructed to stay as still as possible. Figure 1 illustrates our experimental design.

An electronic keyboard was used for the chords arpeggios task. We used the software NIRStim (NIRx Medical Technologies, Glen Head, NY) to present the visual stimuli and the sound that signaled the beginning of each new block and to send the trigger markers to the acquisition software.

Data acquisition

The fNIRS data were collected using a NIRSport8x8 system (NIRx Medical Technologies, Glen Head, NY), consisting of eight sources (760 nm and 850 nm) and seven silicon photodiode detectors. Optodes were placed on the measuring cap with available positions based on the 10–10 international system (Jurcak et al. 2007). Figure 2 illustrates the montage of the 15 optodes covering the prefrontal brain region and the resulting 20 channels (between sources and detectors). A black fabric overcap was placed over the measuring cap

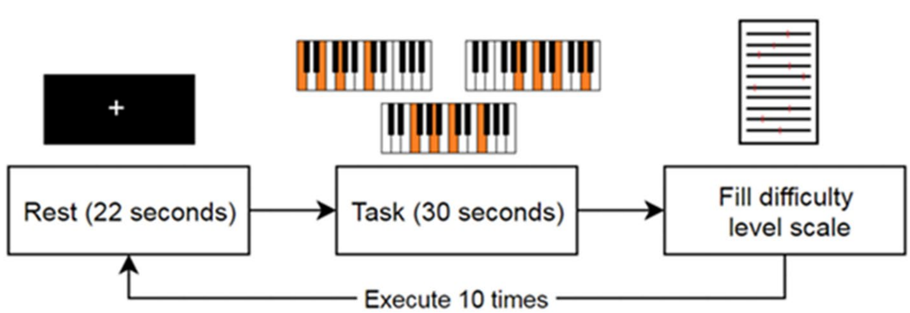

Fig. 1 Experimental design based on ten blocks consisting of (1) rest period (22 s), (2) task (30 s) and (3) difficulty scoring of the respective execution

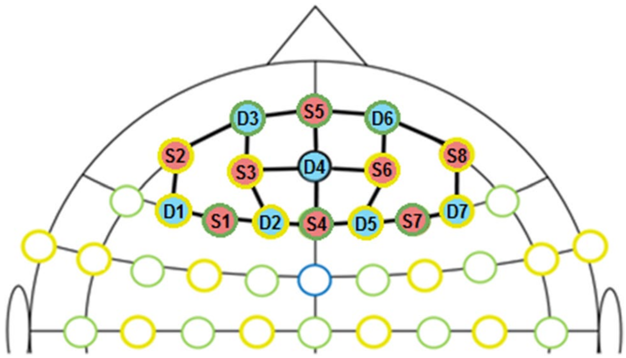

Fig. 2 Illustration of the anterior portion of the measuring cap with available positions based on the 10–10 international system. Light source optodes are depicted in red and identified by the letter "*S*" followed by a number (e.g., "*S*1"), and detectors are blue circles with "*D*" (e.g., "*D*2"). The black lines indicate the measurement channels composed by neighboring optodes

to reduce the luminosity interference and to ensure better contact between the optodes and the scalp.

The acquisition software NIRStar 14.2 (NIRx Medical Technologies, Glen Head, NY) was used to record the raw fNIRS data and to obtain signal quality indicators for the measurement channels following hardware calibration. In the case of channels with poor signal quality during calibration, the contact between the scalp and analogous optodes was immediately adjusted until the overall signal quality was acceptable.

Signal preprocessing

We used the software nirsLAB v2016.05 (https://www.nitrc.org/projects/fnirs_downstate) to preprocess and analyze the fNIRS data. Firstly, we excluded channels in which occurred detector saturation (approximately one channel per subject, on average). Secondly, we truncated the signals before the beginning of the first block and after the end of the last block. We then used a band-pass filter between 0.01 and 0.20 Hz to remove very slow frequency oscillations as well as respiratory and cardiac fluctuations from the data. Finally, we applied the modified Beer–Lambert law (Delpy et al. 1988) to convert the light attenuation as measured with 760 nm and 850 nm in concentration changes of oxygenated and deoxygenated hemoglobin (OxyHb and DeoxyHb, respectively).

Statistical analysis

In an individual-level analysis, we specified a boxcar function, in which the task blocks correspond to the value 1, and the resting blocks correspond to 0 (baseline). To account for the hemodynamic coupling response delay, we used the canonical hemodynamic response function to obtain a convoluted boxcar experimental design. The general linear model (GLM) was applied to obtain the activation beta coefficients for each channel (to quantify the amplitude of OxyHb and DeoxyHb variation induced by the task) of each participant. In this model, we considered the observed hemodynamic signals as the dependent variable and the convoluted experimental design as the independent variable. In a second-level analysis, we use a group GLM to combine all participants' beta coefficients to obtain the group statistical activation map (one sample t test). Since we had 20 different channels for each participant, we used the Bonferroni correction for multiple comparisons. Thus, we considered significant the channels with a p value smaller than $0.05/20 = 0.0025$ to assess a 5% corrected Type I error.

In a post hoc analysis, we extracted the hemodynamic signals from the only channel that presented significant activation in the group analysis (see Fig. 4). We then calculated the block average over the participants to evaluate the hemodynamic response in this channel. In addition, we also computed the average concentration change (mmol/L) and standard error for each task block. Based on these summary statistics for each block, we performed an F-test from a multiple linear regression to evaluate whether the mean activation changes over blocks could be fitted by a polynomial curve. To further explore and identify a peak of activation in the curve, we performed paired t test between the blocks' average.

For the behavioral and subjective assessment, we analyzed the difficulty level subjective scores (a range between zero and one, the latter being the hardest score). Additionally, we evaluated the performance of the volunteers by counting the number of successfully completed arpeggios played during each block, using a recorded video of the experiment. Finally, we computed the average (across subjects) of their performances and the respective standard error.

Results

Figure 3 shows the mean group Oxy and DeoxyHb signal change during the experiment for the statistically significant activated channel identified by the group GLM and highlighted in Fig. 4a. As expected, after the onset of the task, the OxyHb concentration presented an increase while the changes in DeoxyHb were in the opposite direction. Figure 4a depicts the unthresholded group activation map (statistical parametric mapping) for OxyHb. The red highlighted area is the only channel that presented a statistically significant activation during the task based on the GLM analysis. No significant findings were found for DeoxyHb.

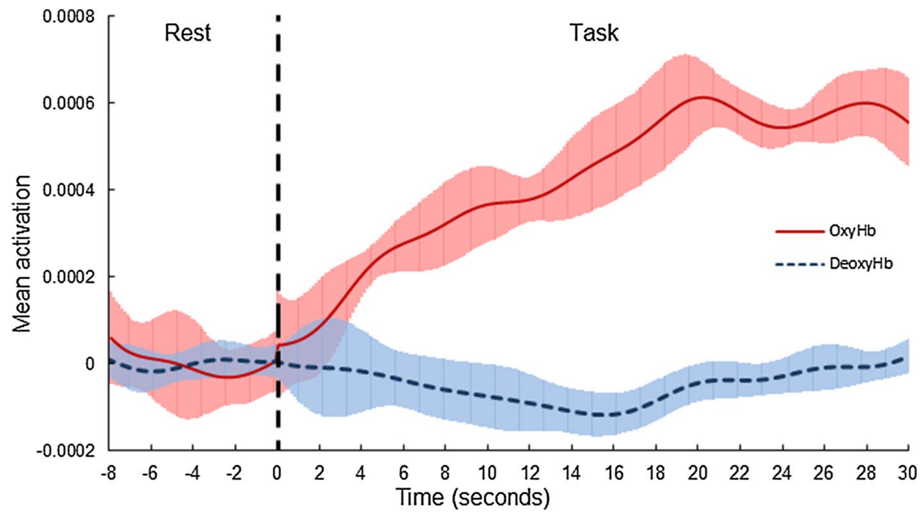

Fig. 3 Mean OxyHb and DeoxyHb activation as the block average signal of the channel highlighted. The vertical dashed line represents the transition from the resting state to the arpeggio task execution. The envelope corresponds to one standard deviation

We depicted the mean activation (OxyHb) for each training block during the task in Fig. 4b. The paired *t* test confirm that the mean activity of the seventh block is greater than the initial blocks (p value <0.05, mainly the second and third blocks; with $t_{12}=2.8852$ and $t_{12}=1.8346$, respectively). Remarkably, the curve increases in the initial blocks until reaching a plateau between the seventh and ninth block and then decreases. A third-order polynomial function was the model that better represents the data according to the multiple linear regression *F*-test ($F_{6,3}=30.8$, *R*-squared: 0.94 and p value <0.001), with statistical significance in the second- and third-order coefficients, as described in Table 1.

Regarding the behavioral data, the mean volunteers performance and the subjective reported difficulty could be fitted by a polynomial function with $R^2=0.989$ (quadratic) and $R^2=0.975$ (cubic). These findings are illustrated in Fig. 4c, d, respectively.

Discussion

In this study, we have used fNIRS to investigate the prefrontal hemodynamic response during a single session of left-hand arpeggio learning in an ecological setting (piano playing). As shown in Fig. 4, fNIRS has the sensitivity to identify a region with a statistically significant hemodynamic response during the execution of the arpeggio task when compared to rest. We infer that this region is located at the right medial orbitofrontal cortex (OFC) (Jurcak et al. 2007). We conjecture that right hemisphere lateralization could be explained by the use of the left hand to play the chords. Moreover, for this region, we found an inverted *U*-shape of the average hemodynamic over the blocks.

As we expected, if we compare the performance of the participants and the respective subjective responses, they are negatively correlated. With more practice, they could play more notes using the same time interval, while they feel that the task became easier than in the previous blocks. However, complementary to our hypothesis of decreasing activation across blocks, we observed an increasing response in the initial training blocks, followed by a plateau and then the expected decrease. This pattern could be represented by an inverted *U*-shape, in which the curvature was statistically tested to fit a third-order polynomial. This result could be interpreted by changes in the cognitive load at the initial blocks, followed by an increase in the control efficiency along the task. The involvement of orbitofrontal cortex might be related to the control of motor responses and error monitoring. This theory is supported by the literature describing this region as a top-down motor controller (Ono et al. 2014). Thus, during the early blocks, the increase in hemodynamic response could be interpreted as the result of a refinement process in line with the declarative stage, which requires a high demand on cognitive functions. In the later blocks, and in line with the procedural stage, the performance of the movement becomes less dependent on this region (automaticity). Besides inhibitory control, the orbitofrontal cortex has been shown to be involved in the acquisition of sequential skills, as discussed by Jackson et al. (2003). While other studies report changes in prefrontal cortex (Hatakenaka et al. 2007; Leff et al. 2008; Ono et al. 2015), our research shows changes in the OFC, a region whose function is little discussed during motor skill acquisition paradigms.

In addition to these findings and the contribution as a new research using fNIRS during motor learning, our research presents a more ecological approach to the study of cognitive control during the early phase of learning new skills. We simulated a design closer to what people would find in their daily lives, with participants sitting on chairs and being able to move their arms freely. Our finding suggests that brain activation response to cognitive functions can have

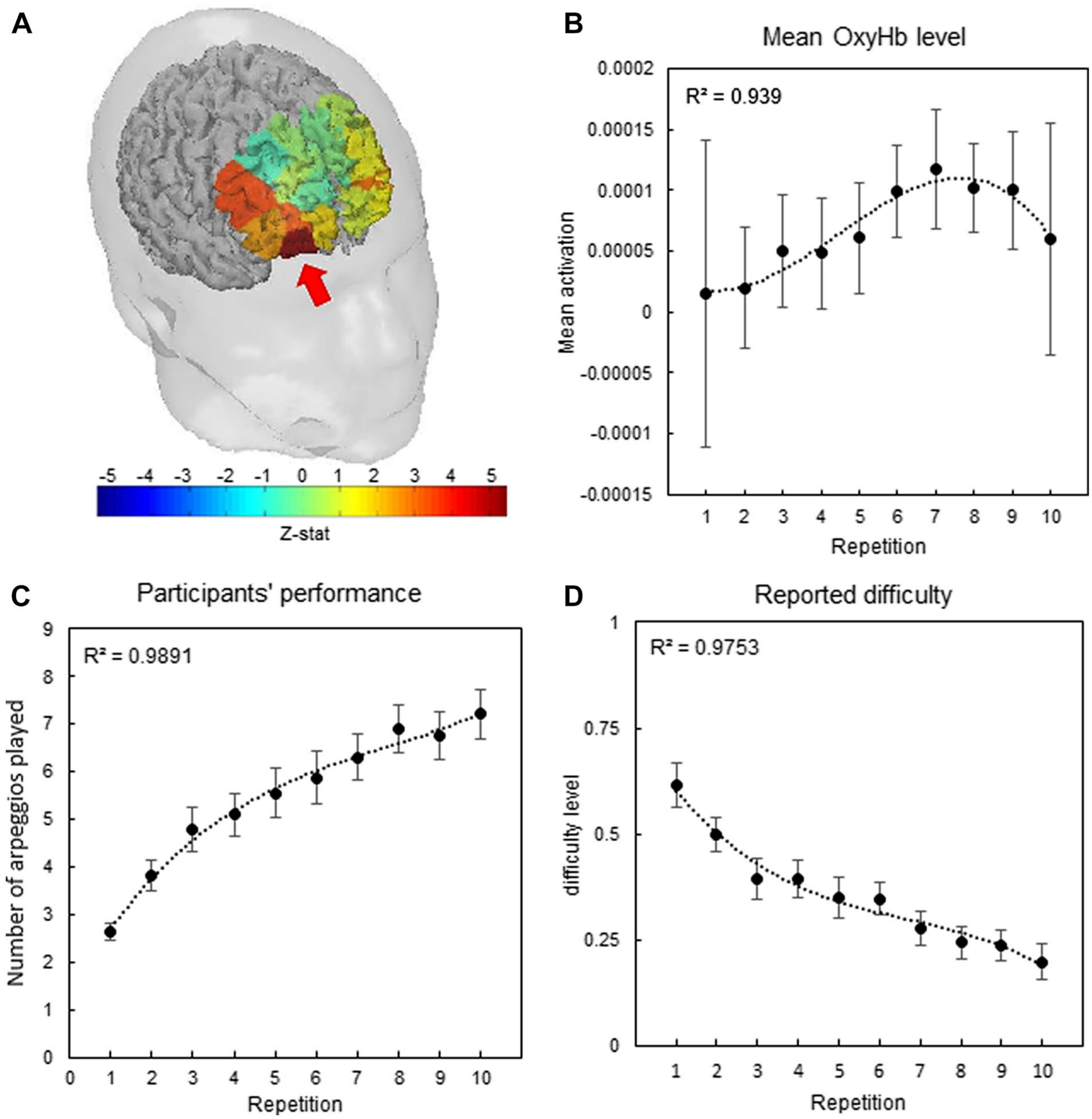

Fig. 4 **a** Group analysis activation map (unthresholded) highlighting the only channel that had a statistically significant response during the arpeggio task when compared to rest. **b** Fit of a third-order polynomial model of oxyhemoglobin concentration across blocks. **c** Performance across blocks, indicating the number of arpeggiated chords executed. **d** Subjective reported difficulty after each block

Table 1 Multiple linear regression results

Order	Coefficient	SE	*p* value
1	3.026e−05	1.572e−05	0.2330
2	− 2.086e−05	3.243e−06	**0.0255**
3	− 7.176e−07	1.945e−07	**0.0102**

The bold values in the *p* value column highlight the significant coefficients

distinct phases and patterns, and this type of learning does not always follow a monotonic function.

Given that our primary goal was to investigate the PFC and the number of optodes constraint, we did not acquire signals from other brain regions. Thus, the brain coverage in this study is limited to this region, without any information regarding other lobes. As discussed in the literature (Jäncke et al. 2000; Krings et al. 2000; Pascual-Leone et al. 1995; Koeneke et al. 2006), motor system regions are also involved during piano learning, and other systems probably also have a role. This is indeed a limitation of our study. Nevertheless, as depicted in Fig. 4a, there is a specificity of the indicated channel in contrast to the others, thus suggesting that our findings are not strongly being influenced by a global activation. Still, it is important to highlight that the main limitation of our study is the potential contamination of systemic artifacts and the impossibility to disentangle them. While the band-pass filter we used may have removed respiratory (~ 0.3 Hz) and heart (~ 1.0 Hz) frequencies, other overlapping signals, such as slow blood pressure oscillations known as Mayer waves (~ 0.1 Hz) and global systemic artifacts, would require more robust signal acquisition and preprocessing methods (Yücel et al. 2016; Kirilina et al. 2013). Therefore, future studies with a greater number of subjects aiming to deeper investigate these initial findings. In addition, a few strategies to validate our results would be to incorporate broader optode arrays covering more regions of interest and to include short-distance channels for direct measurement and removal of superficial signal contributions (Tachtsidis and Scholkmann 2016).

Also, it would be important to further investigate the number of training blocks that would be necessary to achieve the activation plateau and whether this pattern is replicated in all participants and if not why. We believe that the amount of training to achieve this turning point would vary between the participants because, as defined by Kirschner (2002), performance is a consequence of mental load, mental effort and causal factors. While the cognitive load would be high for all participants, since the task that they need to accomplish is the same, the amount of cognitive resources allocated and the personal capacities are heterogeneous.

As a conclusion, our findings suggest that fNIRS is a feasible and promising technique to study cognitive control in real-life situations involving learning, through the investigation of the prefrontal cortex activation.

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