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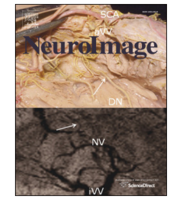

Frontotemporal oxyhemoglobin dynamics predict performance accuracy of dance simulation gameplay: Temporal characteristics of top-down and bottom-up cortical activities

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ABSTRACT

We utilized the high temporal resolution of functional near-infrared spectroscopy to explore how sensory input (visual and rhythmic auditory cues) are processed in the cortical areas of multimodal integration to achieve coordinated motor output during unrestricted dance simulation gameplay. Using an open source clone of the dance simulation video game, Dance Dance Revolution, two cortical regions of interest were selected for study, the middle temporal gyrus (MTG) and the frontopolar cortex (FPC). We hypothesized that activity in the FPC would indicate top-down regulatory mechanisms of motor behavior; while that in the MTG would be sustained due to bottom-up integration of visual and auditory cues throughout the task. We also hypothesized that a correlation would exist between behavioral performance and the temporal patterns of the hemodynamic responses in these regions of interest. Results indicated that greater temporal accuracy of dance steps positively correlated with persistent activation of the MTG and with cumulative suppression of the FPC. When auditory cues were eliminated from the simulation, modifications in cortical responses were found depending on the gameplay performance. In the MTG, high-performance players showed an increase but low-performance players displayed a decrease in cumulative amount of the oxygenated hemoglobin response in the no music condition compared to that in the music condition. In the FPC, high-performance players showed relatively small variance in the activity regardless of the presence of auditory cues, while low-performance players showed larger differences in the activity between the no music and music conditions. These results suggest that the MTG plays an important role in the successful integration of visual and rhythmic cues and the FPC may work as top-down control to compensate for insufficient integrative ability of visual and rhythmic cues in the MTG. The relative relationships between these cortical areas indicated high- to low-performance levels when performing cued motor tasks. We propose that changes in these relationships can be monitored to gage performance increases in motor learning and rehabilitation programs.

Introduction

Functional near-infrared spectroscopy (fNIRS) is a relatively new tool that allows for recording concurrent behavioral and cortical activities. NIRS can be employed as a noninvasive low-cost optical technique for monitoring tissue oxygen saturation, changes in hemoglobin volume and, indirectly, brain/muscle blood flow and muscle oxygen consumption (Ferrari and Quaresima, 2012; Ferrari et al., 2004). The general compatibility of fNIRS with current fMRI data collection and analysis techniques including the use of general linear model and event related design further increases the appeal of fNIRS as an important tool for functional neuroimaging (Ferrari et al., 2004). fNIRS is also more compatible than fMRI when studying populations of infants, elderly, and patients with psychoneurological problems (Hoshi, 2003). There are several benefits of employing fNIRS over other more traditional brain recording techniques such as fMRI: first, fNIRS allows subjects to behave in a more natural way while undergoing a scan. Next, fNIRS can employ multiple channel recording of the cortex, which can be observed and manipulated through the behavior of subjects in real-time. Finally, the temporal resolution of fNIRS is significantly higher than that of fMRI (Cui et al., 2011).

Video games coupled with fNIRS provide researchers the ability to understand how we perceive, integrate, and effectively interact with our real-world environment. Here, we studied a complex sequential

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task with auditory and visual elements in a rhythmic dance video game that required players to select the correct motor act at the correct time while continuously processing visual and auditory cues for current and future decisions and acts. In a previous set of experiments using this dance video game paradigm, we investigated the behaviors of simple stepping and complex variations of gameplay with multimodal audio–visual input (Tachibana et al., 2011). We found that task complexity played a role in shaping fNIRS cortical signal amplitude. Additionally, we found different temporal response patterns in areas of sensory integration: the superior parietal lobe and the temporal association area. The capability of fNIRS to determine these temporal response patterns and relationships between cortical areas suggests that fNIRS imaging of actual, non-reduced or simplified video gameplay allows for a greater understanding of how the brain dynamically regulates the attentional networks involved in the sensory–motor processing.

There is some knowledge of the neural systems involved in integrated sensory–motor behaviors as imaged in finger tapping and piano playing studies using fMRI (Bangert et al., 2006; Baumann et al., 2007; Beauchamp et al., 2004; Hasegawa et al., 2004; Jäncke et al., 2000; Zatorre et al., 2007). Functional cortical activities recorded in these studies suggest that the temporal association area, including the superior temporal sulcus and medial temporal gyrus (MTG), serves as an area of integration of multimodal auditory and visual cues using bottom-up mechanisms in which the system responds to integrated information from the environment (Beauchamp et al., 2004; Fuhrmann Alpert et al., 2008; Tankus and Fried, 2012; Visser et al., 2012). Additionally, the frontopolar cortex (FPC) may serve to coordinate multiple cognitive processes from association cortical areas and forward plan to produce effective motor sequences in top-down fashion (Ramnani and Owen, 2004; Sakai et al., 2002). We therefore observed the interaction between functional activities in the FPC, as part of the top-down executive system, and the MTG, as part of the bottom-up sensory processing system, during a complex dance simulation gameplay. These regions are particularly well suited for fNIRS as frontal and temporal areas have the shortest scalp–brain distance (Cui, 2011).

We hypothesized that activity in the FPC would indicate regulatory mechanisms of top-down motor control; while that in the MTG would be sustained throughout the task to process continuous sensory input in a bottom-up manner. Furthermore, we hypothesized that there would be temporal and pattern differences in the FPC and MTG depending on player proficiency and details of sensory input.

Materials and methods

Subjects

Twenty-six healthy subjects (five females, 23 right-handed) participated in this study (mean age ± standard error = 26.1 ± 1.7 years). The study was approved by the Ethics Committee of the Meiji University School of Science and Technology and all subjects gave written informed consent for participation. Each subject was without neurological or psychiatric illness and had normal or corrected-to-normal vision. Subjects had various levels of experience playing this dance video game; 10 were frequent players (more than 5 h per week and up to several years of playing), four had previous experience playing the game but abstained for more than two years, and the remaining 12 subjects were naïve to the game. Regardless of the wide range of reported experience, the performances of subjects were determined only by their timing accuracy of dance steps through the experimental sessions (see 'Data analysis' for details).

fNIRS measurement

We used a 22-channel fNIRS topography system OMM-3000 (Shimadzu Co., Kyoto, Japan) arranged into a 3 × 5 optical probe array. The array was mounted on an elastic optode cap and positioned over the left prefrontal to the temporal lobes (Figs. 1a–b). The lowest and the most anterior optodes were arranged at Fpz of the international 10–10 system (Chatrian et al., 1985), and the lowest optode row was aligned with the line connecting Fpz–T7. Inter-optode distance was 3 cm for each source detector pair. Data were sampled at 7.9 Hz. The optical probe arrays and optodes were tightly fixed to the cap with a chin-strap to minimize displacements between the head surface and optodes during gameplay. This allowed us to measure reliable fNIRS responses as demonstrated previously (Tachibana et al., 2011). Using a 3D digitizer (PATRIOT, Polhemus, Colchester, VT), we obtained coordinates of all probe positions and the anatomical landmark positions (nasion, inion, auricles and Cz) of each subject immediately before data collection.

Subjects played a dance simulation video game, similar to the commercial game Dance Dance Revolution™ (Konami Corp., Tokyo, Japan) in a block-design fashion. Subjects stood on a dance pad equipped with four buttons consisting of up, down, right, and left arrows and played the song 'Butterfly' (recorded by SMILE.dk). A forty-seven inch television was positioned 1.2 m in front of the subject, providing auditory and/or visual game cues. A series of arrow-shaped visual cues in the up, down, right, or left directions moved from the bottom of the screen to the top. Subjects responded by pressing the correct button at the correct time with their foot when an arrow reached a response area located at the top of the screen (Fig. 1c). We made several modifications to the game using the open source software clone of DDR, StepMania. First,

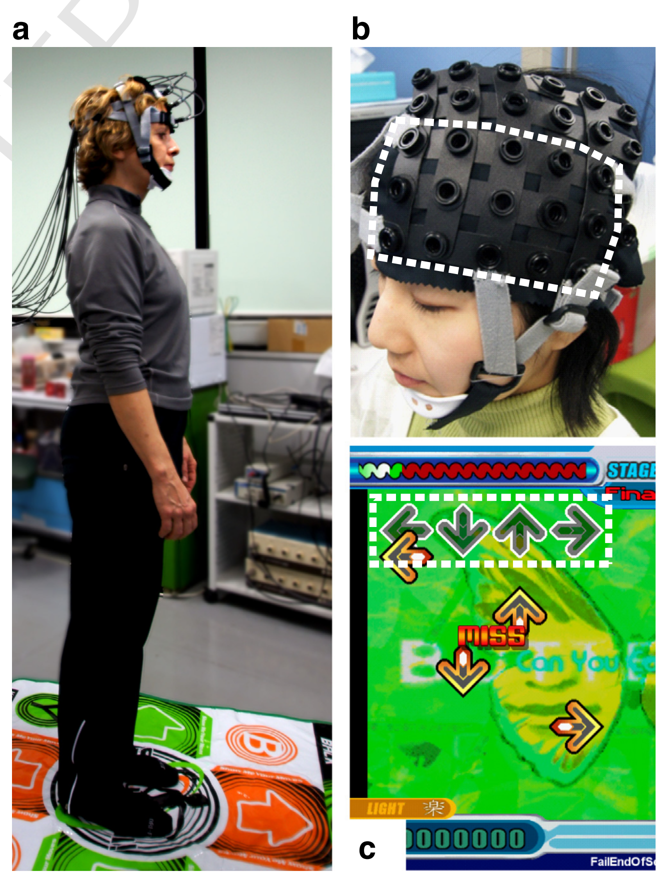

Fig. 1. Instruments of the experiment. a. The subject stood on a dance pad with optical probes of fNIRS on her head. b. Optodes were arranged in the 3 × 5 array (indicated by a dashed-line area), which was mounted on an elastic optode cap. c. Game screen provided visual cues (arrow signs), which scrolled up from the bottom of the screen to the top. The subject responded by pressing the same arrow button on the dance pad at the correct time with his or her foot when it reached a response area (indicated by a dashed-line box). In the "with music (WM)" condition, the timing of steps was to the rhythm of the background music of the game.

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