



Functional near-infrared spectroscopy (fNIRS) of brain function during active balancing using a video game system

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ABSTRACT

Functional near-infrared spectroscopy (fNIRS) is a portable, non-invasive, brain imaging technology that uses low levels of non-ionizing light to record changes in cerebral blood flow in the brain through optical sensors placed on the surface of the scalp. These signals are recorded via flexible fiber optic cables, which allow neuroimaging experiments to be conducted on participants while performing tasks such as standing or walking. fNIRS has the potential to provide new insights into the evolution of brain activation during ambulatory motor learning tasks and standing tasks to probe balance and vestibular function. In this study, a 32 channel fNIRS system was used to record blood flow changes in the frontal, motor, sensory, and temporal cortices during active balancing associated with playing a video game simulating downhill skiing (Nintendo Wii™; Wii-fit™). Using fNIRS, we found activation of superior temporal gyrus, which was modulated by the difficulty of the balance task. This region had been previously implicated in vestibular function from other animal and human studies.

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1. Introduction

Although vestibular function is known to involve sub-cortical and basal structures of the brain, there is increasing evidence of the role of cortical structures in the processing of vestibular related information (reviewed in [1]). In particular, cortical projections of the vestibular network into the temporal–parietal junction and superior temporal gyrus have been implicated in vestibular–ocular control from clinical case studies of individuals with vestibular function affected by lesions in the brain [2]. In addition, research studies utilizing functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) methods have been used to study healthy brain function and have confirmed the existence of several additional cortical regions in the human brain [3]. Most notably, fMRI has been used to show involvement of the parieto-insular vestibular cortex (PIVC), the visual temporal sylvian area (VTS) in the insular cortex, the superior temporal gyrus (STG), the inferior parietal lobe (IPL), the anterior cingulum, and Brodmann area 6a (premotor cortex). Many of the analogues to these regions had been previously found in tracer and electrophysiological studies in monkeys (reviewed in [3]). However, with the exception

of some PET contrast agents (specifically fluorodeoxyglucose; FDG), MRI and PET studies of vestibular function have been very limited largely due to the requirement that the subject lay motionless and in a supine position. Previous studies in humans have been limited to external stimulation of the vestibular system by way of direct stimulation of the inner ear by galvanic [4,5] or caloric irrigation [6,7]. These methods can be performed inside of an MRI or PET scanner, but only allow probes of specific subsets of the vestibular system.

Functional near-infrared spectroscopy (fNIRS) is a non-invasive brain imaging technique that measures blood oxygenation changes similar to fMRI. The technique is based upon the changes in absorption of light emitted by sources onto the surface of the head and measured by detectors. This technique, unlike fMRI and PET, is relatively inexpensive, small, and portable. fNIRS uses fiber optics to carry the signal from a head cap worn by participants to the recording instrument. Thus, fNIRS can be used to record brain activations from tasks such as walking [8] and balance perturbations [9].

In this study, fNIRS was used to record brain activation during a simple balance task which involved simulated skiing using a video game that prompted participants to use shifts in their center-of-mass to steer a character down a simulated slalom ski slope. Previously, similar video game-based exercises had been proposed for the potential of rehabilitation in individuals with motor or vestibular disorders following stroke or other brain injury [10–13]. The goal of this current work was to investigate the hypothesis that

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brain activation in the vestibular cortex (e.g. PIVC, STG, and IPL regions) could be measured using fNIRS during a simple balance task.

1.1. Functional NIRS

Jöbsis [14] first demonstrated the ability to make non-invasive optical measurements of blood flow to the brain. Over the last several decades since his publication, functional near-infrared spectroscopy (fNIRS) has been applied to study a variety of brain regions including the frontal, visual, motor, auditory, and somatosensory cortices (reviewed in [15]). fNIRS is a non-invasive brain imaging modality, which uses near-infrared and visible (red) light to image changes in oxy- and deoxy-hemoglobin through sensors placed on the surface of the head [16,17]. The fNIRS signal is based on changes in the optical absorption of the oxygenated and deoxygenated forms of hemoglobin in the tissue. This provides functional contrast similar to the functional MRI BOLD (blood oxygen level dependent) signal; reflecting changes in regional blood flow to areas of the brain involved in processing functional tasks. Several previous studies (reviewed in [18]) have shown close correspondence between fNIRS and fMRI signals with temporal and spatial (linear) correlations of up to $R = 0.98$ [19] and $R = 0.86$ [20] respectively. Thus, fNIRS can provide functional brain information that is directly reliable to fMRI.

During fNIRS recordings, flexible fiber optic cables are used to deliver low levels of light ($<0.4 \text{ W/cm}^2$) to an arrangement of source positions on the head (see Fig. 1A). Each position contains two (or more) colors of light, which is used to separate absorption changes differentially due to oxy- and deoxy-hemoglobin. Light entering at a source position in the fNIRS head cap will diffuse throughout the tissue. This light will reach down to approximately the outer 5–8 mm of the cortex of the brain based on previous modeling studies (see Fig. 1B). Light is then collected as it exits the head beneath a discrete set of fiber optics that carry light back to photon detectors on the fNIRS instrument (see Fig. 1B). Thus, the amount of light traveling from a light source to reach a detector position is proportional to the absorption of the underlying tissue between that measurement pair. Biological tissue is highly scattering. On average, light in the region of 650–900 nm travels through brain tissue approximately 1/10 mm before scattering (see Fig. 1C). During evoked brain activity, regional changes in blood flow in the active region alter the concentration of oxy- and deoxy-hemoglobin in the brain, which in turn differentially changes the absorption of light at different wavelengths because the two forms of hemoglobin have different optical absorption

profiles. Changes in hemoglobin can be recovered from fNIRS measurements at multiple wavelengths via the modified Beer–Lambert law [21]. By spatially arranging the optical sensors on the head, the location of the brain signal can be approximated as reviewed in Boas et al. [22].

2. Methods

2.1. Subjects

Nine right-handed volunteers with no self-reported balance or mobility disorders (age 18–42; five males/four females) participated in the study. All participants gave written informed consent as approved by the local institutional review board at the University of Pittsburgh.

2.2. Balance task

In this study, fNIRS signals were measured during repeated trials of a commercial video game simulating downhill slalom skiing (Nintendo Wii™; Wii-Fit™ video game). Aside from being a readily accessible platform to initiate a simple balance task, the Wii-Fit™ program has been used in recent research studies investigating the use of video games in physical therapy and rehabilitation following stroke or brain injury [10–13]. The attractiveness of this system is that participants also enjoy doing the task, which is believed to increase adherence to the therapy.

In this game, participants stand on an instrumented balance board that records center-of-mass information, which is used to control the character avatar in the video game. The subjects are first given instructions on how to play the game, which involves the subject to stand on the Wii balance board and move his or her body to go in between gates while going down a virtual ski slope (see Fig. 2A). The subject can control the avatar on the screen by either bringing one's center of balance to the right or left, causing the avatar to go right or left, respectively. The subject can increase the avatar's speed by bringing their center of balance forward on the balance board as well as decrease their speed by bringing their center of balance backwards. Subjects were told that to receive the highest possible score, one would need to go as fast as possible and miss as few gates as possible. In three of the subjects, an additional control task was performed in which the subject watched the video game but was told to stand still during the task. This was done to rule out that the brain response was due to the visual stimulus of the game as opposed to the actual balance task.

The difficulties that were utilized in this study were advanced and beginner. These differ in the amount of time it takes to get down the hill (longer course) as well as the number and distance between slalom gates. For functional scans, the subject was told to stand still for 30 s (standing rest) after which the game was started. A second 30 s standing rest period was added after the subject reached the bottom of the virtual ski slope. The balance task (skiing down the hill) was self-paced depending on the skill and speed of the subject, but generally lasted $37.6 \pm 4.7 \text{ s}$ at the beginner level and $63.1 \pm 6.6 \text{ s}$ at advanced. Each subject performed 6 trials on the beginner level and 8 trials at the advanced level, where each scan contained two trials separated by at least 30 s.

3. NIRS instrumentation

All subjects were recorded using a 32-channel continuous wave fNIRS instrument (CW6 Real-time system; TechEn Inc.; Milford,

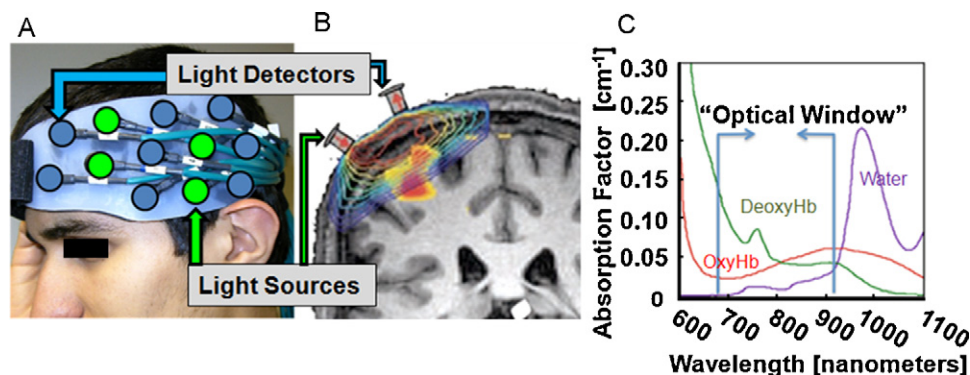


Fig. 1. Functional near-infrared spectroscopy (fNIRS) is used to non-invasively measure changes in oxy- and deoxy-hemoglobin in the brain. In panel (A), a grid of fiber optic-based light sources and detectors is shown mounted on flexible head cap worn by the participant. Each of these source-detector pairs measures light from a diffuse volume of tissue beneath the pair as shown in the model of light propagation (in log-scale) in panel B (described in [19]). This light can reach approximately 5–8 mm into the brain cortex at a source-detector spacing of 3.2 cm. Light at two wavelengths (690 nm and 830 nm) is used to reconstruct changes in oxy- and deoxy-hemoglobin from the intrinsic absorption properties of hemoglobin (panel C) and the modified Beer–Lambert relationship [16].

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