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Validating an image-based fNIRS approach with fMRI and a working memory task

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ABSTRACT

In the current study, we extend a previous methodological pipeline by adding a novel image reconstruction approach to move functional near-infrared (fNIRS) signals from channel-space on the surface of the head to voxel-space within the brain volume. We validate this methodology by comparing voxel-wise fNIRS results to functional magnetic resonance imaging (fMRI) results from a visual working memory (VWM) task using two approaches. In the first approach, significant voxel-wise correlations were observed between fNIRS and fMRI measures for all experimental conditions across brain regions in the fronto-parieto-temporal cortices. In the second approach, we conducted separate multi-factorial ANOVAs on fNIRS and fMRI measures and then examined the correspondence between main and interaction effects within common regions of interest. Both fMRI and fNIRS showed similar trends in activation within the VWM network when the number of items held in working memory increases. These results validate the image-based fNIRS approach.

1. Introduction

Functional magnetic resonance imaging is widely considered to be the gold standard for neuroimaging. It provides excellent spatial resolution that has proven useful in a variety of clinical and non-clinical applications. Nevertheless, fMRI has limitations. It does not provide good temporal resolution and there is debate about the origin and nature of the blood oxygen-level dependent signal (BOLD) (Logothetis et al., 2001). It is also difficult to use fMRI with infants, children, and some clinical and aging populations because participants need to lie still in the scanner. Finally, fMRI cannot be used to scan people who have 'movable' metal fragments in their body.

An alternative neuroimaging technique that overcomes some of these limitations is functional near infrared spectroscopy (fNIRS) (Boas et al., 2014; Ferrari and Quaresima, 2012). fNIRS systems shine near-infrared light at two or more different wavelengths through brain tissue. The two wavelengths of light are differentially absorbed by oxy (HbO) and de-oxy hemoglobin (HbR). Based on this, a localized measure of HbO and HbR concentration in the underlying brain tissue can be determined. Thus, fNIRS provides independent measurements of both chromophores; this has the potential to reveal new insights into neurovascular coupling, particularly given the high temporal resolution of fNIRS. fNIRS can be used with neonates, children, and atypical populations because it is relatively more resistant to motion artifacts. Further, the presence of movable metal fragments is not a limitation with fNIRS. For these reasons, fNIRS has become a neuroimaging tool of choice for these populations. The primary limitation of fNIRS is its poorer spatial resolution relative to fMRI. High quality fNIRS signals can only be obtained from approximately the outer centimeter of cortical tissue. Although this prevents recording from deeper parts of the brain, the spatial resolution obtained in the outer brain tissue is better than that provided by EEG.

fNIRS has been widely used to investigate visual, auditory, motor and cognitive stimulation both in non-clinical and clinical settings (Boas et al., 2014; Bortfeld et al., 2009, 2007; Brigadoi et al., 2012; Wijeakumar et al., 2012a, 2012b). The use of fNIRS in these areas has been spurred forward by validation studies using simultaneous fMRI and fNIRS (Cui et al., 2011; Emir et al., 2008; Erdoğan et al., 2014; Fabiani et al., 2014; Huppert et al., 2006, 2005; Maggioni et al., 2015; Muthalib et al., 2013; Okamoto et al., 2004; Pflieger and Barbour, 2012; Sakatani et al., 2013; Sassaroli et al., 2005; Sato et al., 2013; Steinbrink et al., 2006; Strangman et al., 2002; Tong and Frederick,

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2012; Yücel et al., 2012). These studies have demonstrated good spatial and temporal correlation between both techniques, primarily using tasks that engage the sensorimotor cortices (e.g., finger tapping tasks). Given the increasing number of studies using fNIRS to understand cognition, it is important to validate the use of fNIRS using cognitive tasks to establish whether the correlation between fMRI and fNIRS measures holds beyond the sensorimotor cortex.

One cognitive system that has been extensively studied across the lifespan with functional neuroimaging is visual working memory (VWM). VWM is an important cognitive system that accounts for up to 43% of individual differences in global fluid intelligence (Luck and Vogel, 2013). Previous fMRI studies have identified a fronto-parieto-temporal network (Druzgal and D'Esposito, 2003; Learmonth et al., 2001; Linden et al., 2003; Ma et al., 2014; Pessoa and Ungerleider, 2004; Postle, 2015; Rypma et al., 2002; Todd and Marois, 2005; Todd and Marois, 2004) that is engaged in VWM tasks as well as parts of this network that are differentially activated by parametric manipulations of, for instance, the working memory load (Todd and Marois, 2004). Most regions in this network fall within the cortical depth measured by fNIRS; thus, VWM is a good target for validating the use of fNIRS in cognitive applications (Cui et al., 2011; Cutini et al., 2011; Fishburn et al., 2014; McKendrick et al., 2014; Molteni et al., 2008; Ogawa et al., 2014; Perlman et al., 2015; Tanaka et al., 2014). To date, two validation studies have correlated fMRI and fNIRS measures in VWM tasks (Cui et al., 2011; Sato et al., 2013). Here, we extend these previous efforts by validating a novel image reconstruction approach to fNIRS data.

A central challenge when using fNIRS is that the sensors are placed on the surface of the head, but the questions of interest are about localized activity within the brain volume. Standard fNIRS analysis approaches treat each channel as independent, and significant channel-based effects are often discussed with reference to the 10–20 system of electrode placement. This has several limitations. First, it is difficult to precisely align an fNIRS probe across participants' heads due to variations in head size and shape (Tsuzuki and Dan, 2014). For instance, many studies place the optical probes within a rigid body that is then affixed to the head at a particular reference point in the 10–20 system. Although this places the probe over the correct cortical region, slight rotations of the rigid body on the head can create variations in which cortical regions are measured across participants. This challenge is exacerbated with infants, young children, and clinical populations who have difficulty sitting still.

Second, by treating each fNIRS channel as independent, researchers fail to capitalize on cases where channels record from overlapping regions of cortex. In such cases, weak effects that live at the intersection of channels might not be detected in channel-based analysis. Third, channel-based analyses make it difficult to compare results across studies and to findings from fMRI studies. It would be ideal if we could, for instance, determine whether an effect reported in an fNIRS study was localized in the same region of cortex as a related effect measured with fMRI. Finally, to date, analytic tools developed in the fNIRS literature are often isolated from analytic tools developed in the fMRI literature and vice versa.

One potential solution would be to transform channel-based time-domain fNIRS signals into voxel-based fNIRS activation maps, similar to those reported in fMRI studies. Perlman et al. (2015) used an image reconstruction approach to study activation in response to a VWM task in 3- to 7-year-olds that was based on work by Boas, Culver, and colleagues (Fang and Boas, 2009; Perlman et al., 2015). Here, we build on this and related work (Brigadoi et al., 2015) and ask whether this image reconstruction approach identifies similar clusters of task-related activation within the brain volume measured with simultaneous fMRI.

In the sections that follow, we describe the image reconstruction approach. The pipeline we developed builds on a set of methodological tools that help with the design of fNIRS probe geometries (Wijeakumar et al., 2015). Here, we extend these tools, adding a novel image reconstruction approach to move fNIRS signals from channel-space to voxel-space. We then attempt to validate this approach by examining the correspondence between fMRI and image-based fNIRS in response to a VWM task that we adapted from work by Todd and Marois (2004). First, we examine correlations between HbO and HbR and BOLD activation maps. In a second validation step, we look at whether parametric effects measured with fMRI were also evident in the image-based fNIRS results. An important neural signature that has emerged from the fMRI VWM literature is the increase and gradual asymptote in neural activation levels as the working memory load is increased. In the current study, we will hone in on exemplar clusters that show an effect of working memory load and demonstrate that both fNIRS and fMRI show similar trends in activation levels.

2. Materials and methods

2.1. Subjects

Thirteen (6 Males; M age=25.7; SD=4.2) native English-speaking participants completed the fMRI-fNIRS study. All of them were students at the University of Iowa. All participants had normal or corrected-to-normal vision and signed an informed consent form approved by the Ethics Committee at the University of Iowa.

2.2. Stimuli and task design

We used a Change Detection task. The experimental paradigm was created using E-prime version 2.0 and was run on an HP computer (Windows 7).

Each trial began with a verbal load of two aurally presented letters; see (Todd and Marois, 2004). At the end of each trial, participants were asked to repeat the presented letters to eliminate the possibility of verbal rehearsal of the colors of the stimuli. Following the presentation of the letters, a Sample array of colored squares (24×24 pixels) was presented for 500 ms (randomly sampled from CIE*Lab color-space at least 60° apart). Squares were randomly spaced at least 30° apart along an imaginary circle (100 pixels). The Sample array was followed by a delay of 1200 ms. The delay was followed by the Test array for 1800 ms. The Test array was presented with the same number of colored squares as the Sample array, but the Test array could either match the colors of the Sample array ('Same' trials) or the color of a randomly-selected square was shifted 36° in color space ('Different' trials). Participants had to indicate with a button press if the Test array matched the Sample array (see Fig. 1).

Working memory load was manipulated such that two (Load 2), four (Load 4) or six (Load 6) squares were presented during the Sample and Test arrays. Participants completed five runs of 120 trials (3 runs

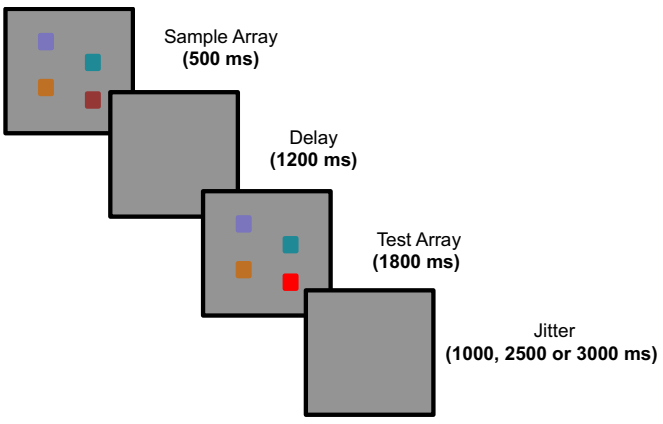

Fig. 1. Change detection paradigm.