NeuroImage 178 (2018) 119–128

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Quantifying fast optical signal and event-related potential relationships during a visual oddball task

Nicole Proulx [a,b], Ali-Akbar Samadani [a,b], Tom Chau [a,b,*]

[a] Bloorview Research Institute, Holland Bloorview Kids Rehabilitation Hospital, 150 Kilgour Road, Toronto, Ontario, M4G 1R8, Canada
[b] Institute of Biomaterials and Biomedical Engineering, University of Toronto, 164 College Street, Toronto, Ontario, M5S 3G9, Canada

ARTICLE INFO

Keywords:
Fast optical signal
Near-infrared spectroscopy (NIRS)
Event-related potential
Electroencephalography (EEG)
Prefrontal cortex
Visual oddball paradigm

ABSTRACT

Event-related potentials (ERPs) have previously been used to confirm the existence of the fast optical signal (FOS) but validation methods have mainly been limited to exploring the temporal correspondence of FOS peaks to those of ERPs. The purpose of this study was to systematically quantify the relationship between FOS and ERP responses to a visual oddball task in both time and frequency domains. Near-infrared spectroscopy (NIRS) and electroencephalography (EEG) sensors were co-located over the prefrontal cortex while participants performed a visual oddball task. Fifteen participants completed 2 data collection sessions each, where they were instructed to keep a mental count of oddball images. The oddball condition produced a positive ERP at 200 ms followed by a negativity 300–500 ms after image onset in the frontal electrodes. In contrast to previous FOS studies, a FOS response was identified only in DC intensity signals and not in phase delay signals. A decrease in DC intensity was found 150–250 ms after oddball image onset with a 400-trial average in 10 of 15 participants. The latency of the positive 200 ms ERP and the FOS DC intensity decrease were significantly correlated for only 6 (out of 15) participants due to the low signal-to-noise ratio of the FOS response. Coherence values between the FOS and ERP oddball responses were found to be significant in the 3–5 Hz frequency band for 10 participants. A significant Granger causal influence of the ERP on the FOS oddball response was uncovered in the 2–6 Hz frequency band for 7 participants. Collectively, our findings suggest that, for a majority of participants, the ERP and the DC intensity signal of the FOS are spectrally coherent, specifically in narrow frequency bands previously associated with event-related oscillations in the prefrontal cortex. However, these electro-optical relationships were only found in a subset of participants. Further research on enhancing the quality of the event-related FOS signal is required before it can be practically exploited in applications such as brain-computer interfacing.

Introduction

Near-infrared spectroscopy (NIRS) is a non-invasive imaging tool which can detect neuronal activity via two types of signals, a slow hemodynamic signal and a fast optical signal. The hemodynamic signal, corresponding to cerebral blood oxygenation variations, is obtained by measuring absorption of near-infrared light through extra-cerebral and cerebral tissue. The hemodynamic signal relates to neuronal activity through neurovascular coupling and has a latency of 4–8 s (Strait and Scheutz, 2014). In contrast, the fast optical signal (FOS) relates directly to neuronal activity and therefore has a latency on the order of milliseconds (Gratton and Fabiani, 2010).

Based on findings from single studies, the FOS is thought to be caused by changes in optical scattering properties of cerebral tissue during neuronal activation (Cohen et al., 1972; Stepnoski et al., 1991; Rector et al., 1997). Stepnoski et al. proposed that the cause of these scattering changes may be attributable to a variation of the neuronal membrane's refractive index during action potential generation (Stepnoski et al., 1991). More recently, Lee et al. determined that the optical response of bulk brain tissue during neuronal activation was related to an increase in neuronal cell volume (Lee and Kim, 2010).

The FOS was first detected non-invasively in the visual cortex of human subjects by Gratton et al. during a visual stimulation task (Gratton et al., 1995a). Gratton et al. found an increase in relative phase delay of the FOS following presentation of visual stimuli and labelled this response as the event-related optical signal (EROS) (Gratton et al., 1995a). This finding of a visually evoked FOS was replicated in subsequent studies by Gratton et al. (Gratton and Corballis, 1995; Gratton and

* Corresponding author. Bloorview Research Institute, Holland Bloorview Kids Rehabilitation Hospital, 150 Kilgour Road, Toronto, Ontario, M4G 1R8, Canada.
E-mail address: tom.chau@utoronto.ca (T. Chau).

https://doi.org/10.1016/j.neuroimage.2018.05.031
Received 7 April 2018; Accepted 11 May 2018
Available online 16 May 2018
1053-8119/

Fabiani, 2003; Gratton et al., 2006; Maclin et al., 2007; Rykhlevskaia et al., 2006; Tse et al., 2010). The same group also detected the FOS in the auditory (Maclin et al., 2003), somatosensory (Maclin et al., 2004), motor (Gratton et al., 1995b; Morren et al., 2004; Parks et al., 2012; Zhang et al., 2012) and prefrontal (Baniqued et al., 2013; Gratton et al., 2009; Low et al., 2006) cortices of the brain using phase delay measurements.

The low signal-to-noise ratio (SNR) and high localization of the FOS (Gratton et al., 2006) has led to debate on FOS detection reliability as well as optimal measurement methods. Using a continuous-wave NIRS instrument, Steinbrink et al. detected a FOS decrease in intensity during median nerve stimulation (Steinbrink et al., 2000). However, further work in this area revealed that the intensity decrease may have been caused by motion artifacts rather than a FOS response (Steinbrink et al., 2005). Steinbrink et al. were also unable to detect a FOS in the visual cortex (Steinbrink et al., 2000). Using frequency-domain NIRS, Wolf et al. were able to detect a FOS in the visual cortex with intensity measurements but not with phase delay measurements (Wolf et al., 2003). Franceschini et al. detected a FOS decrease in intensity during finger tapping but an average of 700–1000 trials was required for detection (Franceschini and Boas, 2004). The same group was unable to find a FOS with measurements directly over the dura mater of monkeys (Radhakrishnan et al., 2009).

To ensure a correspondence between the detected FOS response and neuronal activity, the FOS has been validated spatially with functional magnetic resonance imaging (fMRI) (Gratton et al., 2000) and temporally with electroencephalography (EEG) measurements of various event-related potentials (ERPs) (Low et al., 2006, 2009; Baniqued et al., 2013; Medvedev et al., 2010; Tse et al., 2006; Tse and Penney, 2007; Tse et al., 2013; Huang, 2013), including visually-evoked potentials (VEPs) (Gratton and Fabiani, 2001; Gratton et al., 2006; Sun et al., 2014; Fabiani et al., 2014). The temporal correspondence between FOS and ERP responses in the prefrontal cortex has been verified during Go-NoGo (Medvedev et al., 2010), auditory oddball (Low et al., 2006, 2009; Baniqued et al., 2013; Tse et al., 2006; Tse and Penney, 2007; Tse et al., 2013) and language processing (Huang, 2013) tasks. However, the FOS oddball response elicited in the prefrontal cortex during a visual oddball task, where participants keep a mental count of oddball images (Medvedev et al., 2008), has yet to be validated with ERP measurements.

Despite the presence of ERPs in the prefrontal cortex during oddball stimuli, few studies have used co-localized EEG and NIRS measurements in the prefrontal cortex to explore the correspondence between oddball elicited FOS and ERP responses. Codispoti et al. found a positive ERP response to oddball images at 200 ms latency followed by a 300–500 ms negativity in the prefrontal cortex (Codispoti et al., 2006). Similarly, Low et al. found a frontal ERP negativity 300–500 ms after auditory oddball presentation (Low et al., 2006).

Previous studies have mainly focused on the temporal correspondence between FOS and ERP responses. Following auditory oddball tones, FOS phase delay was found to increase at 350 ms latency, corresponding to the 300–500 ms latency of an ERP frontal negativity and the P300 latency in the parietal cortex (Low et al., 2006). Likewise, Medvedev et al. reported a significant correlation between the 200–350 ms latencies of ERP and FOS negative peaks following target images during a Go-NoGo task (Medvedev et al., 2010). In similar spirit, Tse et al. evaluated the correlation at fixed latencies (Tse and Penney, 2008) and the cross-correlation (Tse et al., 2013) of linear and quadratic trends of fronto-central FOS and ERP responses during an auditory oddball task. In both studies, the linear trend of the ERP mismatch negativity response was found to be correlated with the quadratic trend of the FOS response in the inferior frontal gyrus (IFG) (Tse and Penney, 2008; Tse et al., 2013). Hence, the prefrontal FOS response associated with the visual oddball task has not been validated using co-localized electrical and optical measurements. Additionally, the spectral relationship between ERP and FOS responses has yet to be quantified.

This present study evaluates the temporal and spectral relationships between FOS and ERP oddball responses during a visual oddball task using co-localized EEG and NIRS measurements over the prefrontal cortex. A landmark correlation algorithm was developed to quantify the temporal correlation between FOS and ERP oddball peaks. Spectral relationships were also examined using spectral coherence and Granger causality connectivity metrics. To our knowledge, this is the first study to examine the spectral relationships of the FOS and ERP responses during a visual oddball task.

Methods

Participants

Fifteen adult participants (10 female, mean age: 25.0 ± 3.7 years) were recruited from staff and students at Holland Bloorview Kids Rehabilitation Hospital (Toronto, Canada) and the University of Toronto. All participants were right-handed. Participants had normal or corrected-to-normal vision, were able to read and communicate in English and had no degenerative, cardiovascular or metabolic disorders and respiratory, physical, psychological, cognitive, psychiatric or drug and alcohol-related conditions. Participants were asked to refrain from smoking, and drinking alcoholic or caffeinated beverages 3 h prior to the data collection sessions. Ethics approval was obtained from Holland Bloorview Kids Rehabilitation Hospital and the University of Toronto. Written consent was obtained from each participant.

Instrumentation

NIRS measurements were collected using a frequency-domain near-infrared spectrometer (Imagent Functional Brain Imaging System from ISS Inc., Champaign, IL) at a sampling rate of 62.5 Hz. Five laser diode sources, paired at 690 nm and 830 nm wavelengths, and 4 photomultiplier tube detectors were placed over the participant's forehead using a custom-made leather headband. A black cloth was tied over the headband to block external light. The sources and detectors were located at 3 cm distances as shown in Fig. 1. The source-detector configuration enabled 11 measurement channels of each wavelength across the prefrontal cortex.

EEG measurements were collected using a BrainAmp DC amplifier (Brain Products GmbH, Germany) at a sampling rate of 250 Hz. Six electrodes were placed around the NIRS headband at selected International 10-10 system locations with reference electrodes at the mastoids and a ground electrode at AFz (Fig. 1). Electrodes were placed on the participant's skin with doubled-sided adhesive disks.

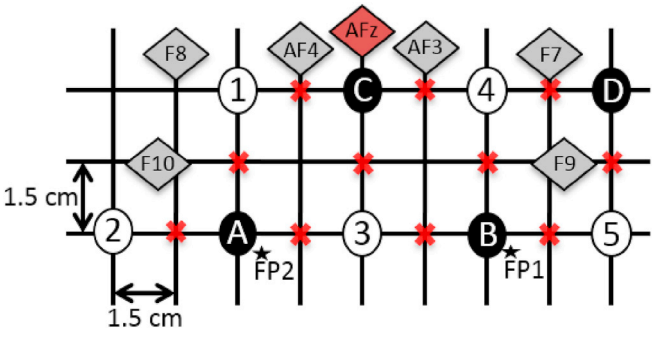

Fig. 1. NIRS source-detector and EEG electrode configurations. Each empty circle, labelled 1–5, represents 2 NIRS sources, at 690 nm and 830 nm wavelengths. Each filled circle, labelled A-D, represents a detector. Measurement locations, i.e. channels, are half-way between sources and detectors and denoted by a red 'X'. EEG electrodes, denoted by grey diamonds, were placed at AF3, AF4, F7, F8, F9 and F10 electrode locations according the International 10-10 system. The ground electrode, denoted by a red diamond, was at AFz and the reference electrodes were at the left and right mastoids.