# Multimodal integration of fNIRS, fMRI and EEG neuroimaging [Letter]

**Makii Muthalib, Abdul Rauf Anwar, Stephane Perrey, Marco Dat, Andreas Galka, Stephan Wolff, Ulrich Heute, Günther Deuschl, Jan Raethjen, Muthuraman Muthuraman**

**Angaben zur Veröffentlichung / Publication details:**

Muthalib, Makii, Abdul Rauf Anwar, Stephane Perrey, Marco Dat, Andreas Galka, Stephan Wolff, Ulrich Heute, Günther Deuschl, Jan Raethjen, and Muthuraman Muthuraman. 2013. "Multimodal integration of fNIRS, fMRI and EEG neuroimaging [Letter]." *Clinical Neurophysiology* 124 (10): 2060–62. https://doi.org/10.1016/j.clinph.2013.03.018.

## Multimodal integration of fNIRS, fMRI and EEG neuroimaging

Investigating human brain function can be improved by employing a multimodal neuroimaging approach. The integration of different non-invasive electrophysiological (e.g., electroencephalography-EEG and magnetoencephalography) and haemodynamic (e.g., functional magnetic resonance imaging-fMRI and functional near-infrared spectroscopy-fNIRS) neuroimaging modalities simultaneously measuring functional brain activation during motor and cognitive tasks compliments each other's limitations (Shibasaki, 2008). Both EEG and MEG measure functional brain activity directly by detecting the variations in electrical and magnetic fields, respectively, produced by neuronal activity across the scalp. Both fMRI and fNIRS measure functional brain activity indirectly via changes in the blood oxygenation level-dependent (fMRI-BOLD increase) contrast signal and concentration changes in oxygenated (fNIRS-$O_2$Hb increase) and deoxygenated (fNIRS-HHb decrease) haemoglobin, respectively, which are related to an increase in regional cerebral blood flow subsequent to increased neuronal activity (i.e., neurovascular coupling). Since each neuroimaging modality has its own characteristic features especially in terms of spatial and temporal resolution, previous studies have simultaneously measured combinations of two out of the modalities during motor and cognitive tasks, and found good relationships between the techniques (Cui et al., 2011; Shibasaki, 2008; Steinbrink et al., 2006).

A better understanding of the relationships between these electrical and hemodynamic neuroimaging modalities will clarify how neural changes (EEG) are reflected in metabolic and vascular signals (fNIRS and fMRI) in (a)typical neurophysiological conditions that do (not) fit standard models of neurovascular coupling. Simultaneous EEG-fMRI measurements allow to investigate within the whole brain the hemodynamic changes (fMRI) correlated with neuronal activity (EEG). Integrating fNIRS responses with EEG-fMRI could accurately characterize the neurovascular coupling in cortical regions selected as part of the brain network involved in motor and cognitive behaviour. For instance, simultaneously recorded EEG and electromyography (EMG) signals, known to provide information on the changes of the cortico-muscular coherence over time during motor tasks (Muthuraman et al., 2012; Raethjen et al., 2007), can be utilised to determine the relationship between the evolving cortico-muscular coupling (EEG-EMG) and neurovascular coupling (fMRI and fNIRS) in motor tasks.

The aim of this study was to determine for the first time the concordance between three non-invasive neuroimaging modalities (fNIRS, fMRI and EEG-EMG coherence) simultaneously measuring the coupled electrical and hemodynamic consequences during simple and complex motor tasks.

A 38 year-old healthy male performed finger tapping (FT), simple finger sequence (SFS), and complex finger sequence (CFS) motor tasks with his right hand in a block design (10 blocks with 30s task and 30s rest = total time of 600s). The FT task consisted of simple tapping of the index finger in a rhythmic fashion at a rate of 2–5 taps per second. The SFS task consisted of sequential tapping of the index, middle, ring and fourth finger against thumb, and the CFS task consisted of sequential tapping of index, ring, middle and fourth finger against the thumb. The experimental equipment consisted of a 3T MRI scanner (Philips Achieva, Philips, The Netherlands), and fMRI-compatible 256-channel EEG (GEO300, EGI, USA) and 24 channel fNIRS (Oxymon MkIII, AMS, The Netherlands) systems. Four fNIRS probes were placed in the EEG cap in the spaces around the electrode at C3 (according to the EEG 10–20 system), which corresponded to the primary sensorimotor cortex (SMC1) contralateral to the movement (See Fig. 1A). Surface EMG was recorded from the forearm extensors and flexors on the right dominant hand (See Fig. 1B). A fiducial marker was placed between the fNIRS probes over the SMC1, which was confirmed by MRI-T1 images (See Fig. 1C). fMRI-BOLD activation maps were determined using the SPM8 toolbox (http://www.fil.ion.ucl.ac.uk/spm) using a threshold of $p < 0.05$, and fMRI-BOLD time series data (sampling frequency: 2.5 s = total 240 time points in 600 s) from the SMC1 was extracted from a region of interest identified by a sphere of radius of 17.5 mm around the local maxima of activation (See Fig. 1D). fNIRS ($O_2$Hb and HHb) time series data (sampling frequency: 0.1 s) from the 4 channels were down-sampled to the fMRI time series of 2.5 s, providing 240 time points for comparison. To identify the best fNIRS channel to use for the correlation analysis, simple correlation was calculated between fNIRS and fMRI over each of the 10 blocks. Scalp EEG electrodes surrounding the SMC1 (C3) and ipsilateral motor cortex (C4) were chosen for estimating the scalp level EEG coherence over time with the right extensor EMG using the dynamical coherence analysis (DCA) method (Raethjen et al., 2007). The DCA analysis was used to calculate scalp level EEG-EMG coherence by estimating the coherence spectra using moving 30-s windows with an overlap of 27.5 s, resulting in an apparent time resolution of 2.5 s. The DCA and dynamic imaging of coherent sources (DICS) analysis (Muthuraman et al., 2012) methods were used to calculate source level EEG coherence over time with the right extensor EMG (See Fig. 1E). DICS was used to identify the highest coherent activated region in the subjects brain for the individual motor task frequency (3 Hz), as expected this was the SMC1 in all the three motor tasks. A spatial filter algorithm was then used to extract the source level EEG time series from the SMC1 and then its dynamical coherence with EMG signals was calculated using the DCA method. Spearman's correlation was used to determine the relationship between fMRI (BOLD), fNIRS ($O_2$Hb and HHb), and EEG (scalp level and source level EEG coherence) over the 10 blocks (240 time points) of the 3 motor tasks.

Fig. 1F shows the time courses of fMRI (BOLD), fNIRS ($O_2$Hb and HHb), and EEG (source level EEG coherence) signals over the 10 blocks of the FT task. As shown in Table 1, fNIRS-$O_2$Hb and fNIRS-HHb were significantly correlated positively and negatively, respectively with fMRI-BOLD and source level EEG-EMG coherence during the three motor tasks. These findings on simultaneously integrating fNIRS, fMRI and EEG measurements confirm and extend previous research using combinations of two of the three

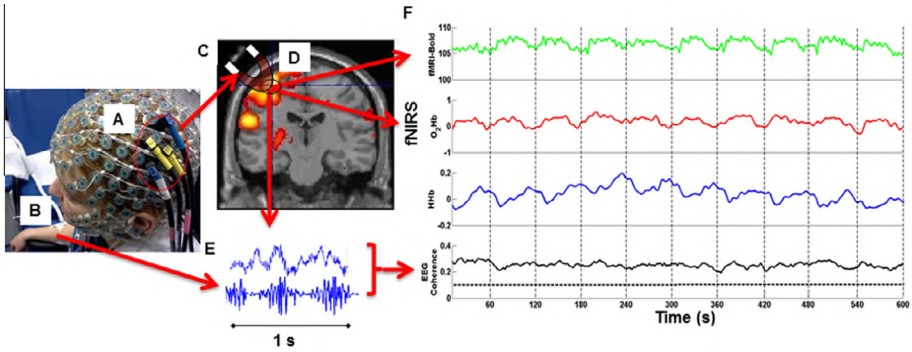


**Fig. 1.** Method of determination of primary sensorimotor cortex (SMC1) activation by fNIRS, fMRI and EEG neuroimaging modalities during the finger tapping (FT) task of the right hand. (A) Shows the fNIRS probe setup around the C3 electrode of the EEG cap and (B) shows the EMG electrodes on the right wrist extensor/flexor muscles. (C) Shows the estimated fNIRS transmitter and receiver locations on the scalp and projected sampling region on the SMC1. (D) Shows the spherical region of interest on the SMC1 for extracting the fMRI-BOLD time series. (E) Shows the source level EEG (upper blue trace) and EMG (lower blue trace) time series. (F) Shows the time courses of fMRI-BOLD (green trace), fNIRS-$O_2$Hb (red trace) and fNIRS-HHb (blue trace), and the source level EEG coherence (black trace) signals over the 10 blocks (vertical dashed lines) of the FT task.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
fNIRS, fMRI and EEG correlations of primary sensorimotor cortex activation during finger tapping (FT), simple finger sequence (SFS) and complex finger sequence (CFS) motor tasks of the right hand.

| Neuroimaging modality | | Motor tasks | | |
|---|---|---|---|---|
| | | FT | SFS | CFS |
| fNIRS-$O_2$Hb | fMRI-BOLD | 0.22*** | 0.58*** | 0.28*** |
| | Source level EEG | 0.19** | 0.15** | 0.58*** |
| | Scalp level EEG | 0.63*** | – | – |
| fNIRS-HHb | fMRI-BOLD | −0.43*** | −0.40*** | −0.26*** |
| | Source level EEG | −0.13* | −0.13* | −0.12* |
| | Scalp level EEG | −0.50*** | – | – |
| fMRI-BOLD | Source level EEG | −0.13* | −0.14* | −0.58*** |
| | Scalp level EEG | −0.66*** | – | – |

* $p < 0.05$.
** $p < 0.01$.
*** $p<0.001$.

neuroimaging modalities (Cui et al., 2011; Shibasaki, 2008; Steinbrink et al., 2006).

A novel aspect of this study was the finding of a clear relationship between cortico-muscular coupling measured using EEG and EMG with neurovascular coupling detected using fNIRS and fMRI during motor behaviour. The scalp level EEG showed correlations with fNIRS and fMRI only during the simple motor task (FT) but the complex motor tasks (SFS and CFS) showed the need of source level EEG analysis (DICS method) in order to correlate cortico-muscular to neurovascular coupling. fMRI activation maps showed a greater area of activation in the SMC1 for the complex tasks vs. the simple task (Anwar et al., 2012). Therefore, one reason that the scalp level EEG did not correlate during the complex motor tasks may be that the activated region of the SMC1 was not as focal compared to FT; consequently by identifying the local maxima in the SMC1 using the EEG source analysis gave a better coherence to the EMG during the complex motor tasks than the scalp level (C3) EEG.

The present findings provide further support for fNIRS being an appropriate substitute for fMRI for studying cortical activity related to cognitive and motor tasks (Steinbrink et al., 2006). Moreover, unlike fMRI, fNIRS is invariant to electrical and magnetic fields produced by invasive electrical deep brain stimulation, and non-invasive transcranial direct current stimulation and transcranial magnetic stimulation, therefore fNIRS can be used to map cortical neurophysiological correlates of motor and cognitive performance in patients concurrently receiving these electrical and magnetic stimulation treatments.

In conclusion, our findings show good temporal correlations between fNIRS, fMRI and source level EEG data collected simultaneously from the SMC1 during simple and complex motor tasks. The capacity of non-invasive neuroimaging techniques to monitor concurrently the temporal progression of physiological changes induced by motor tasks may prove highly beneficial for the development and optimization of both basic neuroscience and clinical applications.

## Acknowledgements

Dr. Muthalib, Mr. Anwar, Dr. Galka, Prof. Deuschl, Prof. Raethjen, Prof. Heute and Dr. Muthuraman were partly or fully supported by the German Research Foundation SFB855 Grant "Magnetoelectric Composites – Future Biomagnetic Interfaces".

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Makii Muthalib *
*Department of Neurology, Christian-Albrechts University, Kiel, Germany*
*Movement to Health (M2H), Euromov, Montpellier-1 University, 700 Avenue du Pic Saint Loup, 34090 Montpellier, France*
*Movement Neuroscience Program, Queensland University of Technology, Brisbane, Australia*
* Tel.: +33 411759066; fax: +33 411759050.
*E-mail addresses*: makii.muthalib@gmail.com,makii.mu thalib@univ-montp1.fr

Abdul R. Anwar
*Department of Neurology,*
*Christian-Albrechts University,*
*Kiel, Germany*
*Department of Digital Signal Processing and System Theory,*
*Christian-Albrechts University,*
*Kiel, Germany*

Stephane Perrey
*Movement to Health (M2H),*
*Montpellier-1 University,*
*Montpellier, France*

Marco Dat
*Artinis Medical Systems,*
*Zetten, The Netherlands*

Andreas Galka
*Department of Neuropediatrics,*
*Christian-Albrechts University,*
*Kiel, Germany*

Stephan Wolff
*Department of Neuroradiology,*
*Christian-Albrechts University,*
*Kiel, Germany*

Ulrich Heute
*Department of Digital Signal Processing and System Theory,*
*Christian-Albrechts University,*
*Kiel, Germany*

Gunther Deuschl
*Department of Neurology,*
*Christian-Albrechts University,*
*Kiel, Germany*

Jan Raethjen
*Department of Neurology,*
*Christian-Albrechts University,*
*Kiel, Germany*

Muthuraman Muthuraman
*Department of Neurology,*
*Christian-Albrechts University,*
*Kiel, Germany*