Introduction

- Brain-computer interface (BCI) applications often use either invasive electrodes or non-invasive measures (e.g., fNIRS). An alternative is functional near infrared spectroscopic (fNIRS) imaging, which has the spatial resolution needed to localize activation in the somatosensory cortex [1], and it is more mobile than other non-invasive methods [2].

- In addition to direct measures of activation [1], and to studies of structural connectivity (explored by, e.g., diffusion tensor MRI [3]), steadily increasing use is being made of methods for estimating functional(effective) connectivity. Indeed, given value $\mathbf{x}_n = \text{capillary resting net oxygen extraction}$, $\mathbf{y}_n = \text{vasodilatory signal decay rate}$, $\mathbf{f} = \text{autoregulatory feedback rate constant}$, the mean capillary transit time $\mathbf{t}$, and $\mathbf{w}$ = vaso dilatory signal decay rate, $\mathbf{E}_n$ = capillary resting net oxygen extraction.

- A PubMed search of papers published in the last five years yielded 3077 (371) on the subject of functional(effective) connectivity, 819 (84) on fMRI-based.

- Effective connectivity algorithms, such as dynamic causal modeling, or DCM [4], frequently make assumptions regarding system behavior (e.g., neurovascular coupling model) that are not necessarily valid. Also, in practice there isn’t a way to confirm that the connection drawn from a connectivity analysis is correct.

- Here we present a testbed for fNIRS imaging, which includes a stable solid-state phantom containing embedded electrochromic and electric-dipole elements. The behavior of the internal devices are user-controlled and programmable, such that they can be used to mimic position-dependent and time-varying hemodynamic and biostatic responses.

- Additional aspects of the testbed include a support environment for the phantom, including integrated sensing headgear and a robust data analysis environment that can integrate connectivity based on DCM.

- As a demonstration of the utility of the testbed, we have carried out a set of experiments and data analyses—based on and extending a simulation study reported in Ref. 5—to assess the robustness of results obtained from DCM-based model-selection computations.

Methods

- Solid-State Dynamic Phantom (Fig. 1)
  - Anthropomorphic (or other biological forms seen in Fig. 5), light, and resistant to biological degradation
  - Matrix consists of silicone and saline-based biopolymer
  - Electrochromic cells (ECC) mimic wavelength-dependent hemodynamic responses
  - Bipolar dipoles mimicking biostatic responses
  - Connectors for user interface and controlling various displays options, including Automated Anatomical Labeling (AAL) method employed in all experiments.

- Sensing and Headgear
  - NIRx-NIRScout imaging system
    - Accommodates up to 32 detectors and 48 sources, time-multiplexed with adjustable gain switching [2,6]
    - 16 detectors and 16-dual wavelength superluminescent LEDs operating at 760 and 850 nm were used
  - NIRx DYNOT Compact imaging system
    - Accommodates up to 32 detectors and 9 sources, time-multiplexed with adjustable gain switching
    - 30 detectors and 9-dual wavelength diode-laser sources operating at 760 and 830 nm were used
  - In another case a modified Easy-Cap from Brain Products (Fig. 2) [7]

- NAVI-SPM and Mapping Environment
  - NAVI-NIRx, SPM-EEG, Visualisation, Analysis, Visualization and Imaging (Fig. 3) [8,9]
  - Extensive data-handling functionality
  - FEM-based image formation (Fig. 4)
  - Various display options, including Automated Anatomical Labeling (AAL) method employed in SPM [10]

- GLM methods used in support of individual (level 1) and group (level 2) analyses for detection of neuroactivation

- Atlas-based mapping environment in support of human and macaque studies (Fig. 5)

- Serves as basis for rapid 3D image reconstruction

- Dynamic Causal Modeling / DCM
  - Mathematical strategy for analyzing functional neuroimaging data in order to infer effective connectivity

- Chosen over approaches that are exclusively data-driven, because model selection can be reliably guided from prior knowledge [11]

- Experimental study of DCM model selection accuracy, based on analysis of fNIRS time series imaging data

- Bilinear mathematical model of temporally evolving neuronal activity [5]:

  $\mathbf{A} \cdot \mathbf{x} = \mathbf{B} \cdot \mathbf{E} + \mathbf{u} \quad | \quad \mathbf{B} = \mathbf{C} \cdot \mathbf{u}$

  $\mathbf{x} = \text{time-varying neural activity in a user-specified number of cortical regions}$

  $\mathbf{E} = \text{vaso dilatory signal decay rate}$, $\mathbf{f} = \text{autoregulatory feedback rate constant}$, the mean capillary transit time $\mathbf{t}$, and $\mathbf{w} = vaso dilatory signal decay rate, $\mathbf{E}_n$ = capillary resting net oxygen extraction.

Methods (cont.)

- A, B and C matrices in Eq. (1) specify the effective connectivity, or interactions (e.g., fMRI). An alternative is functional near infrared spectroscopic (fNIRS) imaging, which has the spatial resolution needed to localize activation in the somatosensory cortex [1], and it is more mobile than other non-invasive methods [2].

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- Acknowledgments

- References

- Conclusion

Results

- Five sets of fNIRS measurements were carried out, using ECC driving functions computed for each of the models in Fig. 6.

- Averaging across data with NIIDSP using GLM at effective Level-1 RPM, yields statistical parametric maps, such as those shown in Fig. 9.

- A special mean time series result was generated for each of the driving functions (e.g., Fig. 8), subsequently, these served as the input for DCM reverse-problem computations.

- For each of each time-driven data, all five models in Fig. 6 were evaluated as effective connectivity hypotheses. However, comparisons of the computed Bayesian evidence (Ref. 5) for each hypothesis, the correct connectivity hypothesis was selected in two of the five cases:

- Each column, the tabulated numbers are the Bayesian evidence for each hypothesis, as a percentage of the maximal evidence value.

- Results for the other three cases are affected by unexpected confounding factors; a tendency for DCM to overfit the data noise in some (Model 2), but not all, cases; inherent degrees of freedom to obtain a good fit to the data in the case of the simplest model (Model 4); absence of a unique solution in the case of the most complex model (Model 5).

Conclusion

- For functional imaging-based DCM, just as for other inverse problems, it is necessary to ensure that the problem is well-posed/conditioned. Accordingly, an important consideration is how to appropriately constrain the problem. The availability of an experimental testbed, such as the one described here, facilitates the development and testing of regularization schemes for fNIRS-based DCM.