Development of Whole-Brain Activity Measures to Aid in Optimization of BCI Performance

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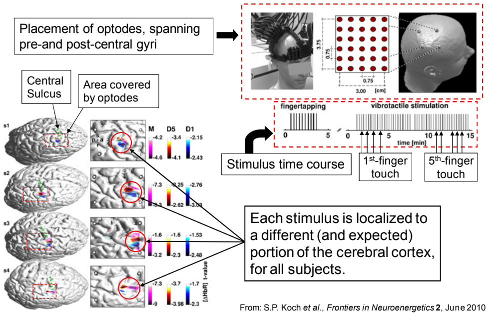
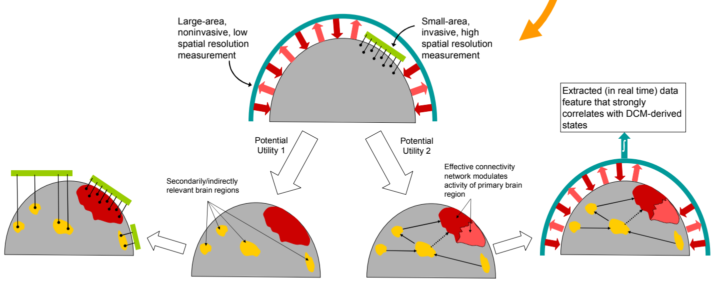
B.M.I. – implant interprets neuroactivity signals; decides what action the person/animal wishes to perform; actuates it



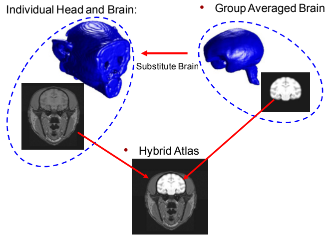
From: S.P. Koch *et al.*, *Frontiers in Neuroenergetics* **2**, June 2010

1) Non-invasive modalities give access to a larger fraction of the brain

2) Performing both direct (EEG and indirect (fNIRS) measurements maximizes the accessible brain volume, plus each one can serve as a co-variate for interpretation of the other.



Hybrid Atlas



Prior (Human Head) Anatomical Mapping Work

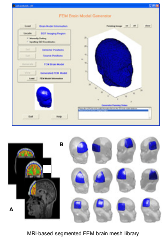
1. 3D FEM brain model generator:

Supports easy specification of user-defined image operators for a selected sensing array configuration.

a. MR-based FEM model library:

- Establish segmented FEM brain atlas from MRI of selected subject(s).
- Divide brain into 25 overlapping regions, each comprising 3000-3500 nodes, with each region having a surface area of 50-75 cm^2 and a maximum depth of up to 5 cm.
- Compute solutions to forward diffusion problem, using Type III boundary conditions, for each of nearly 400 outer surface nodes per region.
- Compute joint intensity probabilities for all possible source-detector combinations, to generate associated Jacobian matrix (~160,000 pairs/ROI).

b. User interface



MRI-based segmented FEM brain mesh library.

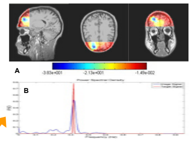
Software Validation

2. Software validation:

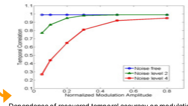
a. Sensitivity to Expected Experimental Uncertainty:

Findings demonstrate that mapping errors vary from 3-10 mm with the largest error occurring at edge of S/D region.

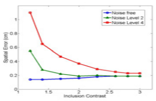
b. Phantom Study: Introduce Hb signal at known location and dynamics.



(A) Reconstructed GLM log p-value images from **dynamic phantom** experimental data. (B) Power spectral density distributions of LC cell driven signal (red) and reconstructed signal (blue).



Dependence of recovered temporal accuracy on modulation amplitude (*i.e.*, inclusion has time-varying absorption) and data noise level.



Dependence of recovered spatial accuracy on inclusion/background absorption contrast ratio.

4) Detailed anatomical picture of subject's head improves solution accuracy and spatial resolution
   a) Imaging operators take the details of the inhomogeneous, irregularly shaped, medium into account
   b) A single, standard head, that data from individual subjects is projected onto, minimizing effects of individual variation
   c) All of the advantages gained from using normalized difference strategies apply

5) Well-characterized methods for analyzing time series (e.g., GLM) can be used to accurately identify which brain regions consistently participate in planning ("thinking about") and performing the task under study

Functional connectivity

- Seed-voxel correlation analyses (e.g., GLM)
- Eigenimage analysis
  - ◊ Principal Component Analysis (PCA)
  - ◊ Singular Value Decomposition (SVD)
  - ◊ Partial Least Squares (PLS)
- Independent Component Analysis (ICA)

Pros:
◊ useful when we have no model of what caused the data (*e.g.*, sleep, hallucinatons)
Cons:
◊ no mechanistic insight into the neural system of interest
◊ inappropriate for situations where we have *a priori* knowledge and experimental control over the system of interest

Effective connectivity

- Structural Equation Modelling (SEM)
- Psycho-physiological interactions (PPI)
- Multivariate autoregressive models (MAR) & Granger causality techniques
- Kalman filtering
- Volterra series
- Dynamic Causal Modelling (DCM)

Pros:
◊ useful when we have a model of what caused the data
Cons:
◊ inappropriate if cerebral dynamics do not closely approximate theoretical assumptions underlying the method

DCM: Distinguished from others:
◊ accommodating the nonlinear and dynamic aspects of neuronal interactions
◊ framing the estimation problem in terms of perturbations that accommodate experimentally designed inputs

3) While GLM integrates over time, techniques such as DCM can be used to derive a high level of information – effective connectivity – from detailed differences between the timings of responses in different regions.
   a) Premium on SNR and undistorted imaging data (recovered value proportional to what is actually present)

- Central idea:

Brain ⟷ Deterministic nonlinear dynamic system

Effective connectivity is parameterized in terms of coupling among unobserved brain states (*e.g.*, neuronal activity in different regions)

- Objective:

To estimate the parameters by perturbing the system and measuring the response

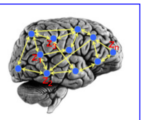
Neuronal states: $z(t)=\begin{bmatrix} z_1(t) \\ \vdots \\ z_n(t) \end{bmatrix}$

State equations: $\dot{z}=\frac{dz}{dt}=\begin{bmatrix} \dot{z}_1 \\ \vdots \\ \dot{z}_n \end{bmatrix}=\begin{bmatrix} f_1(z_1,\cdots,z_n,u,\theta_1) \\ \vdots \\ f_n(z_1,\cdots,z_n,u,\theta_n) \end{bmatrix}$

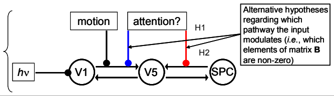
in general $\dot{z}=F(z,u,\theta)$

u: external input

$\theta=[\theta_1,\cdots,\theta_n]$: system parameters, specify the nature of the interactions



Visual Stimulus Paradigm

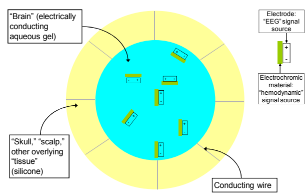


	Motion Effect, Attention Effect	Volume Doubled	Sphere → Cube, Volume Preserved	Center Moved by 1/2 Radius	Original Radius Doubled
H 1:	0.409, 0.176	0.386, 0.162	0.384, 0.167	0.321, 0.121	0.321, 0.147
H 2:	0.400, 0.345	0.381, 0.329	0.378, 0.337	0.327, 0.293	**0.319, 0.334**

Stability Analysis. Note that interpretation of DCM parameters is based on trends (*e.g.*, motion effect > attention effect), not on the exact numerical values.

The relative magnitudes of the computed parameters has flipped (motion effect < attention effect).

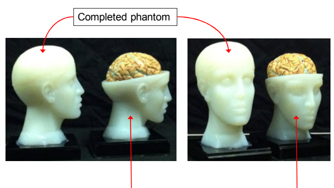
fNIRS/EEG Dynamic Phantom: concept



6) Dynamic phantom – provides unequivocal mechanism for assessing the accuracy of an effective connectivity algorithm (e.g., DCM)
   a) Always know what The Right Answer is, because that's input
   b) Both the modulatory effects among brain regions, and the magnitude and timing of the hemodynamic response function, can be experimentally controlled

c) Testbed for assessing the impact of including/leaving out regions (e.g., ones identified from the noninvasive measurement) on the performance of the effective connectivity computations

fNIRS/EEG Dynamic Phantom: example



Brain template (subsequently replaced by aqueous-gel "brain" cast) positioned inside a silicone "overlying tissue" cast

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