

Theory of the Relation between Human Brain Activity (MEG) and Hand Movements

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Scope

- Recent research has demonstrated that a robust relation exists between *brain activity* and the *movement profile* produced. Brain activity has been shown to correlate strongly with movement velocity independent of movement direction and mode of coordination.
- Using a recently developed *field theoretical* model of large-scale brain activity itself based on neuroanatomical and neurophysiological constraints we show here how these experimental findings relate to the *field theory* and how it is possible to reconstruct the movement profile via spatial and temporal integration of the brain signal.

Outline/Introduction

Data: behavioral data : finger movement profile
MEG Brain activity

Experimental Observations :

➡ relation of brain activity with the finger motion

Spatiotemporal Dynamics :

➡ Haken's approach to the analysis of complex systems:
phenomenological study of the multidimensional time series
via *biorthogonal* decomposition

Modeling the integration of Neural activity

➡ Jirsa's and Haken's *field theoretical* approach

Results:

reconstruction of the finger motion profile from the brain signal

predict the motor signal from the measured MEG data

Perspectives:

Computational Procedures that readily and accurately reveals relationships between movement and brain activity can simplify the inquiry into how CNS controls movements and might be employed for clinical and technical applications, e.g. to control prosthetic and robotic devices

THE EXPERIMENTAL OBSERVATIONS

Behavior experiment (Kelso et al. : *Nature*,1998)

movement of the right index finger coordinated with a visual metronome at **1 HZ**

four task conditions: *Flexion* vs *Extension*

and in / anti - phase with the metronome beats: *synchronization* vs *syncopation*

100 movement cycles for each task.

recorded data

- finger displacement as pressure changes in an air cushion

- brain activity using a 68-channel full-head magnetometer (CTF), at SF of 250 HZ

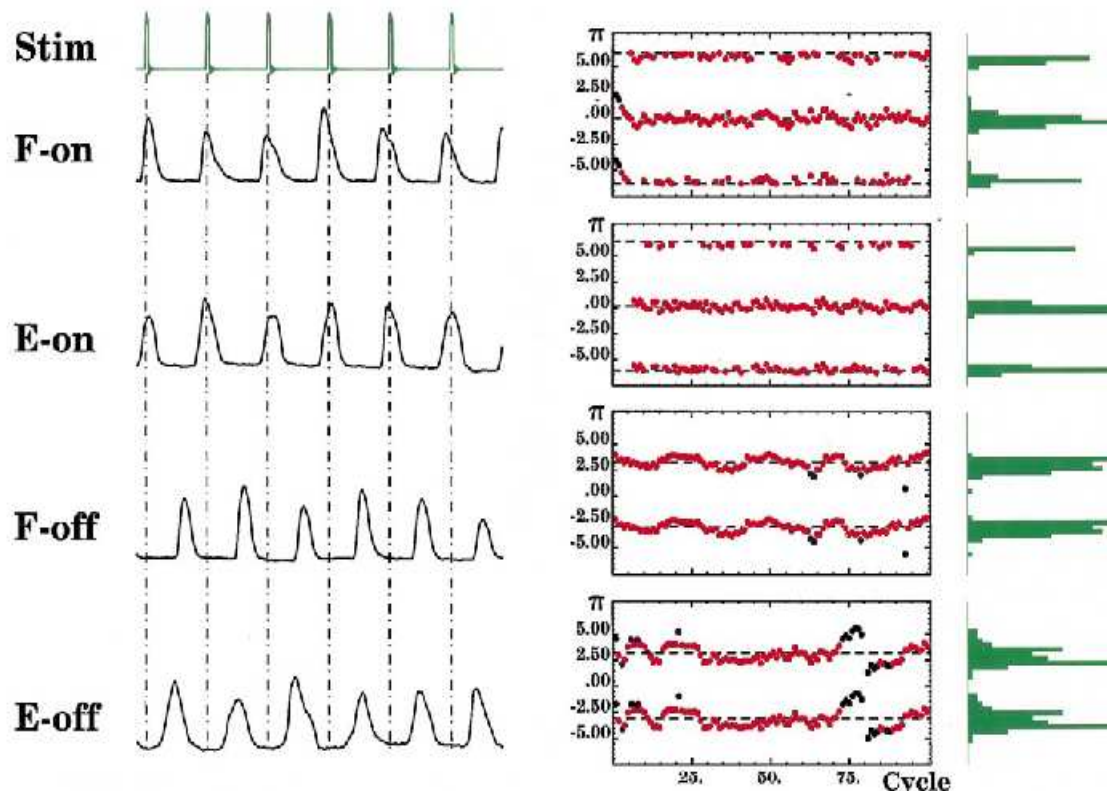


FIG. 1. Relation between stimulus and movement signal for all task conditions.

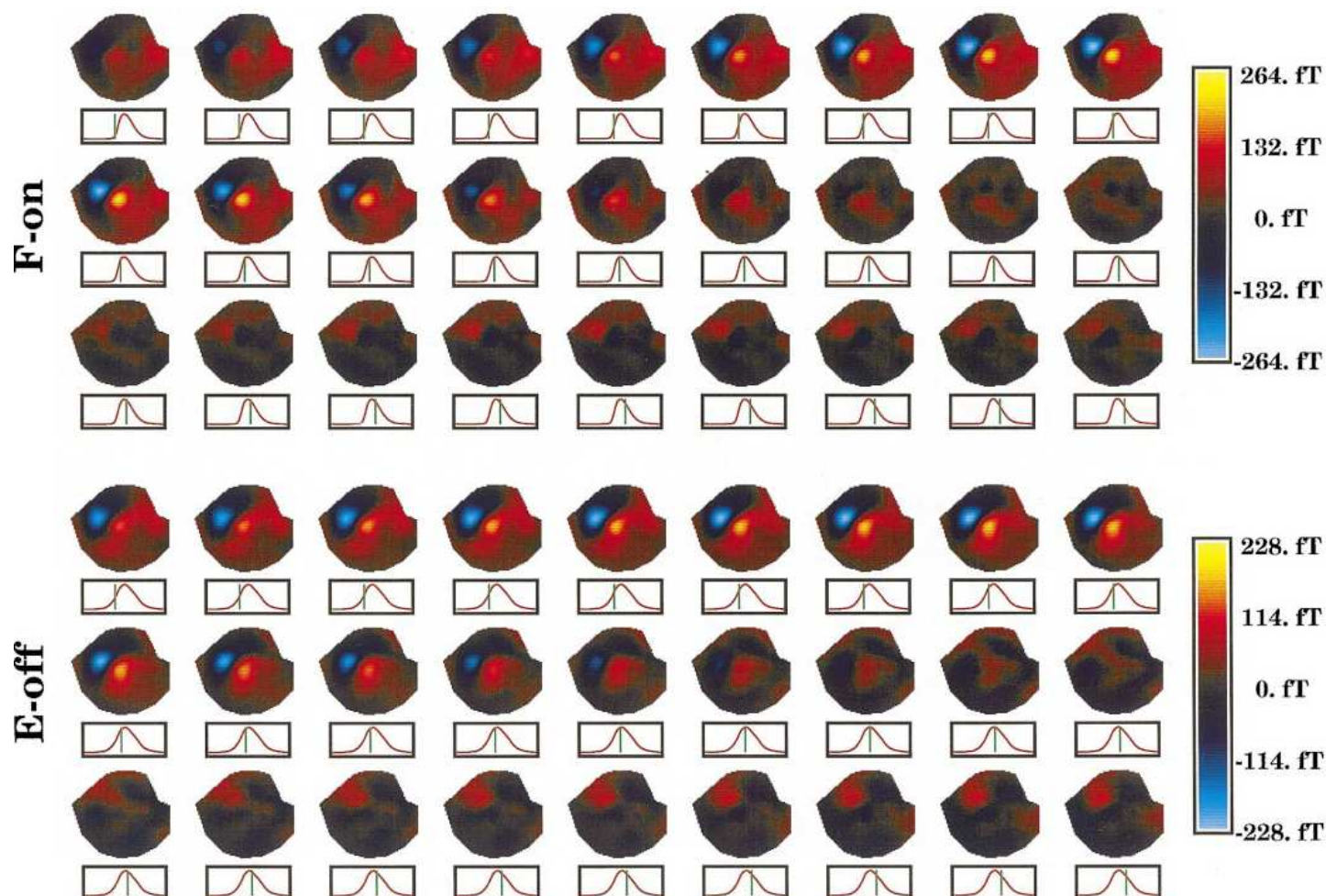
Left: in the on conditions the maximum amplitude coincides with the metronome flashes

Middle: Relative phase between the stimulus and the maximum of the movement amplitude. Circles plotted in blue deviate more than 60° from the required (average) phase and were discarded.

Right: Histograms of the relative phases. **The variance is smaller in the on-conditions indicating higher stability for the synchronized movement compared to syncopation.**

Behavioral and **Brain** data were averaged on a cycle-by-cycle basis with respect to maximum finger displacement for each tasks.

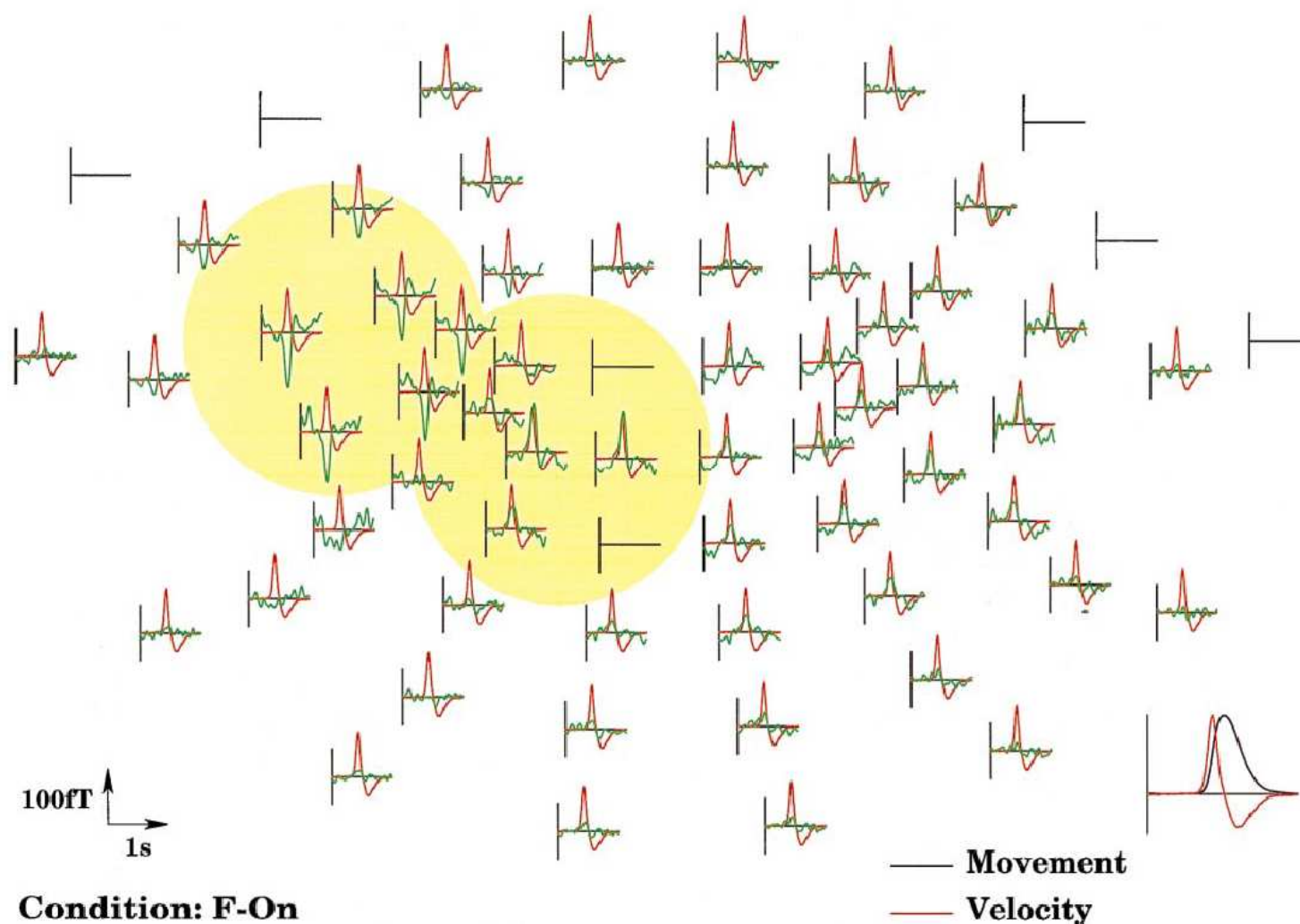
The temporal evolution of brain activity during the finger movement is represented with a sequence of topographic maps:



the a green bar indicating the brain pattern's location within the cycle of movement

- ➡ Near movement onset a strong dipolar field arises over the left hemisphere. After maximum displacement is reached a dipolar field with reversed polarity and smaller amplitude is visible.
- ➡ These dipolar structures appear to be independent of the direction of movement (flexion vs extension).
- ➡ They also appear to reach their maximum magnitude at the time points of the peak movement velocity, i.e., where the slope of the movement profile is greatest.

Highlighting the correlation of finger movement velocity with the averaged brain signals



Overlap between brain signals (green) and movement velocity (red) in single channels. The correlation (or anti-correlation) is extremely high in channels inside the highlighted area. On the bottom right the relation between the movement profile (blue) and movement velocity (red) is shown.

BRIDGE BETWEEN THEORY AND EXPERIMENT: ANALYSIS OF SPATIOTEMPORAL BRAIN SIGNALS

a spatiotemporal pattern $Y(x,t)$ can be decomposed into

spatial modes $u^{(i)}(x)$ and corresponding *time-dependent amplitudes* $f^{(i)}(t)$

$$Y(x,t) = \sum_i f^{(i)}(t) u^{(i)}(x) \quad , \text{ e.g. via PCA}$$

or in discrete form $Y_k(t) = \sum_i f^{(i)}(t) u_k^{(i)}$, where k the #sensor

Due to the strong correlation between finger movement velocity and brain signal a decomposition in two spatial modes of the spatiotemporal pattern $Y(x,t)$ is sought such as $f^{(i)}(t)$ coincide with the finger displacement signal and the movement velocity signal, i.e.


$$\underline{Y}_k(t) = r(t) v_k^{(1)} + r'(t) v_k^{(2)}$$

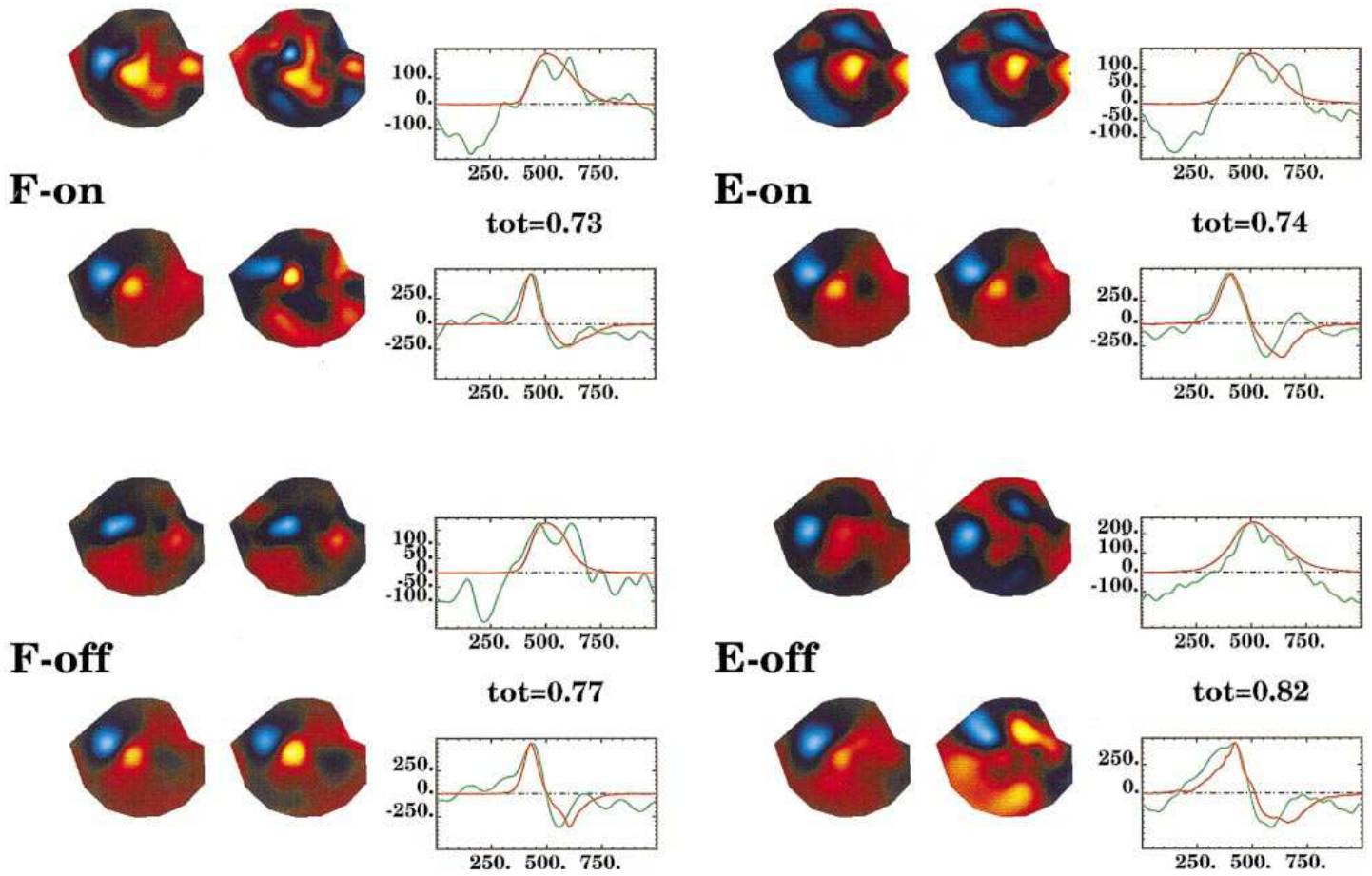
The two spatial modes $v_k^{(1)}$ & $v_k^{(2)}$ are determined by *linear regression*;

since they are not orthogonal the adjoint vectors $v_k^{(1)+}$ & $v_k^{(2)+}$ are calculated and *biorthogonal* expansion is performed:

$$\underline{Y}_k(t) = f^{(1)}(t) v_k^{(1)} + f^{(2)}(t) v_k^{(2)}$$


$$\text{with } f^{(1)}(t) = \underline{Y}(t) \cdot \mathbf{v}^{(1)+} \quad \text{and} \quad f^{(2)}(t) = \underline{Y}(t) \cdot \mathbf{v}^{(2)+}$$

 The quality of the reconstruction of the original spatiotemporal pattern, measured by the **tot** = $\text{var}(\underline{Y}_k(t) - Y_k(t)) / \text{var}(Y_k(t))$ is very high in all the tasks



Biorthogonal decomposition of $Y(x,t)$ into spatial modes fitting finger movement and velocity

Reconstruction of the brain signal from the two spatial modes $V_k^{(1)}$ & $V_k^{(2)}$ for the F-on task.

 **Most of the spatiotemporal dynamics is reproduced.**

Connecting Field Theory and experiment

On macroscopic level (cm & 100 msec), the measured signal/field takes the form:

$$Y(x,t) = a \int_G dX f(x-X) \mathcal{S} \left[\rho Y \left(X, t - \frac{|x-X|}{u} \right) + \mathbf{p} \left(X, t - \frac{|x-X|}{u} \right) \right], \quad f(x-X) = \frac{1}{2\sigma} e^{-\frac{|x-X|}{\sigma}}$$

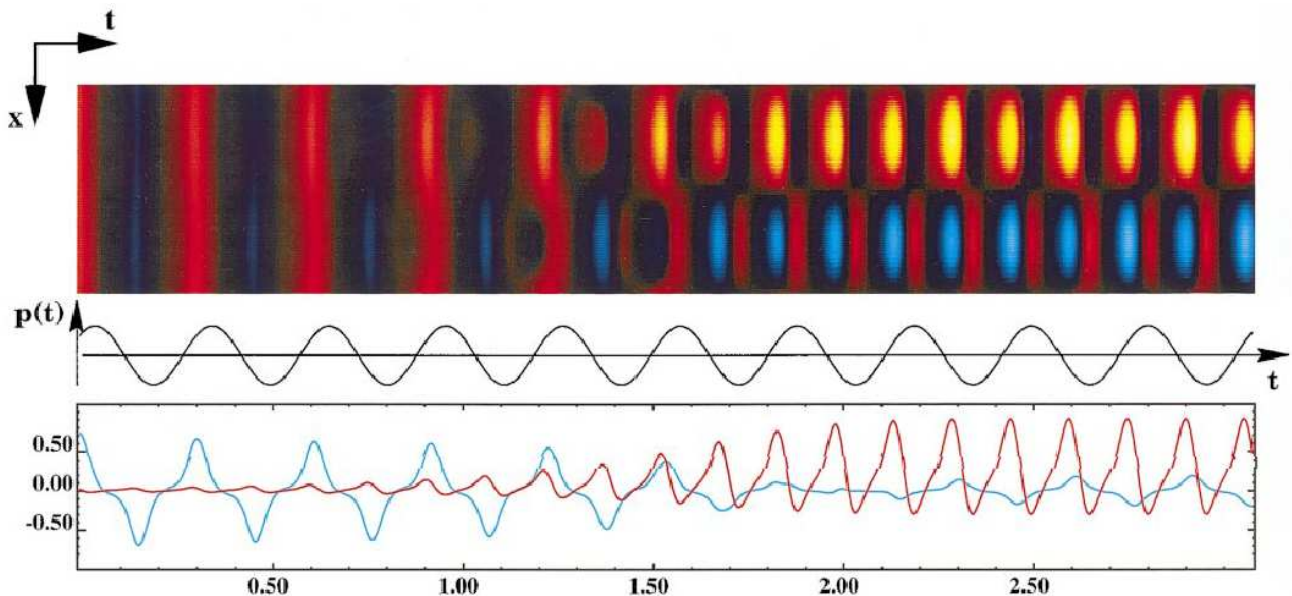
$Y(x,t)$: average amplitude of dendritic currents at location x in the cortical sheet G .
 it is the weighted sum of activity received from all other locations X in G
 and the input \mathbf{p} at X (e.g. sensory inputs).

u : the velocity that the activity is spread with.

$f(x-X)$ is the distribution function of the connection strength between x and X

ρ : the fiber density and a : synaptic weight

in a reformed version, as a partial differential equation in one dimension, it has been used to explain a behavioral situation where the subject switches from syncopated coordination mode to synchronization when the rate of stimulus is systematically increased (from 1Hz to 3Hz).



pre-transition



post-transition

Here, the main objective is to relate the *field theory* formulation with the experimental observations by deriving an equation of the form

$$Y(x,t) = r(t) v^{(1)}(x) + r'(t) v^{(2)}(x)$$

and relate all parameters to measured data

-the concept of *functional units* is used to combine the **internal brain dynamics**, with the *sensory inputs* and the *motor outputs*

Functional input unit :

the time course of the activity of neural population that receives afferent excitation

$$p(x,t) = \beta^{in}(x) \int_{to}^t f(t-\tau) N^{in}(r(t)) d\tau$$

$\beta^{in}(x)$: the spatial localization in the cortical sheet G

$f(t-\tau)$: defines the temporal convolution of the nonlinear transformed movement $r(t)$

Functional output unit :

the output signal is the weighted sum of activity over the corresponding brain area

$$r(t) = \int_G \beta^{out}(x) \int_{to}^t g(t-\tau) N^{out}(Y(x,t)) d\tau$$

$\beta^{out}(x)$: the spatial localization in the cortical sheet G

$g(t-\tau)$: temporal transfer function of the nonlinear transformed cortical activity

- spatial localizations $\beta^{in,out}(x)$ and

- transfer functions $f(t-\tau)$, $g(t-\tau)$ will be related to the recorded data

with the approximations: $\beta^{in}(x) \approx \beta^{out}(x) = \beta(x)$ due to large spatial scale
and N^{in} , N^{out} being linear functions

the relation between the motor signal $r(t)$ and the brain activity $Y(x,t)$ becomes:

$$\int_{to}^t f(t-\tau) r(\tau) d\tau = \int_{to}^t f(t-\tau) d\tau \cdot \int_{to}^{\tau} g(\tau-\tau') d\tau' \cdot \int_G \beta(x) Y(x,\tau') dx$$

with Taylor expansion of $r(\tau)$ it yields

$$\int_{t_0}^t f(t-\tau) [c_0 r(t) + c_1 \dot{r}(t) + \dots] d\tau = \int_{t_0}^t f(t-\tau) d\tau \cdot \int_{t_0}^{\tau} g(\tau-\tau') d\tau' \cdot \int_G \beta(x) \mathbf{Y}(x, \tau') dx \quad (1)$$

from the experimental data two spatial modes modulated

by the movement signal and the corresponding velocity can approximate the MEG signal :

$$r(t) v^{(1)}(x) + r'(t) v^{(2)}(x) \approx \mathbf{Y}(x, t) \Rightarrow \text{(multiplying by } \beta(x) \text{ \& integrating)}$$

$$r(t) \int_G \beta(x) v^{(1)}(x) dx + \dot{r}(t) \int_G \beta(x) v^{(2)}(x) dx \approx \int_G \beta(x) \mathbf{Y}(x, t) dx \quad (2)$$

◆ Comparing (1) & (2), $c_n \rightarrow 0$ for $n \geq 2$

and temporal convolutions in r.h.s. equal the identity operator

◆ Identifying the spatial function $\beta(x)$, representing the input-output unit, as the dominating pattern, i.e. the mode $v^{(2)}(x)$

$$r(t) \int_G v^{(2)}(x) v^{(1)}(x) dx + \dot{r}(t) \int_G v^{(2)}(x) v^{(2)}(x) dx \approx \int_G v^{(2)}(x) \mathbf{Y}(x, t) dx \quad (3)$$

in the discrete version and assuming normalization of the $v^{(2)}$ mode (3) reads

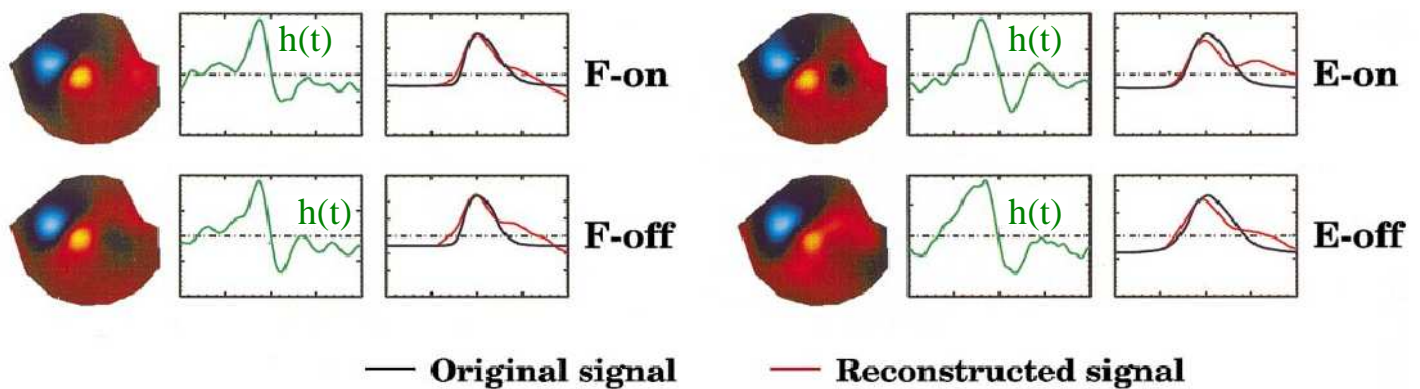
$$r(t) \mathbf{v}^{(2)} \cdot \mathbf{v}^{(1)} + r'(t) = h(t) = \mathbf{v}^{(2)} \cdot \mathbf{Y}(t) \quad (4)$$

◆ the motor signal $r(t)$ takes the form of a driven overdamped harmonic oscillator; the solution of (4) for large t is given:

$$r(t) = ct \int_{t_0}^t h(\tau) e^{-(\mathbf{v}^{(2)} \cdot \mathbf{v}^{(1)}) \cdot (t-\tau)} d\tau$$

expressing the movement time series in terms of the brain activity (via $h(t)$)

reconstruction of the movement profile from the underlying neural activity for all task conditions.



The reconstructed movement profile fits the experimentally observed movement particularly well in the active phase of the movement represented by its positive flank. Discrepancies mainly occur after peak displacement and are probably due to the sensory feedback which is not accounted for in the present formulation.

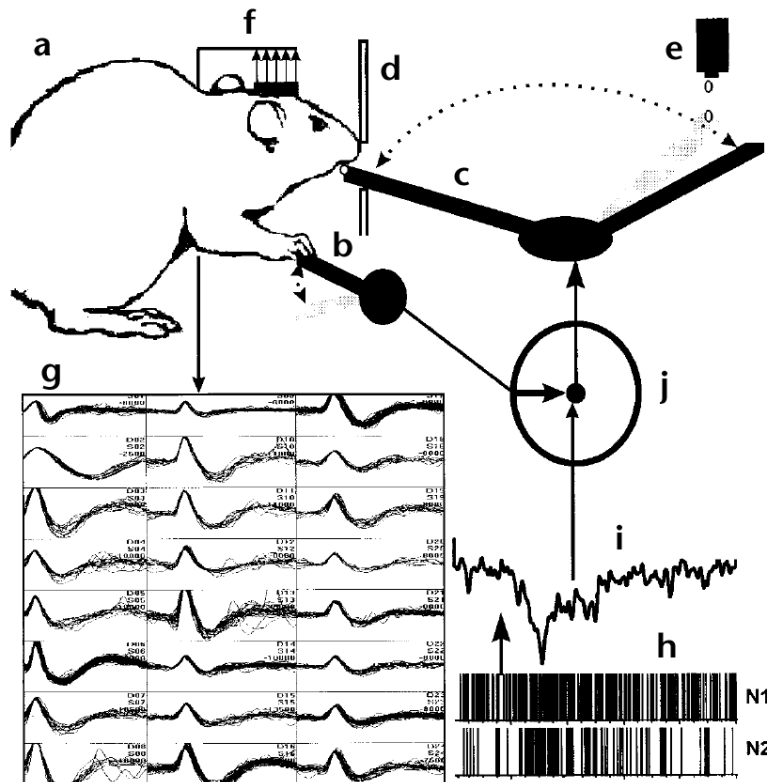
Conclusions

- “ The brain does indeed generate signals that reproduce the actual movement trajectory (independent of the direction).

Discussion / Commentary by J.Sanes

- ❶ inquiry of additional movement features, e.g. direction.
- ❷ multiple-joint movements
- ❸ incorporation of the known primary motor cortex organization
- ❹ single-trial resolution

Real-time control of a robotic arm by neuronal ensembles



Chapin et al. *Nature Neuroscience*. 1999: 2(7), pp664-670

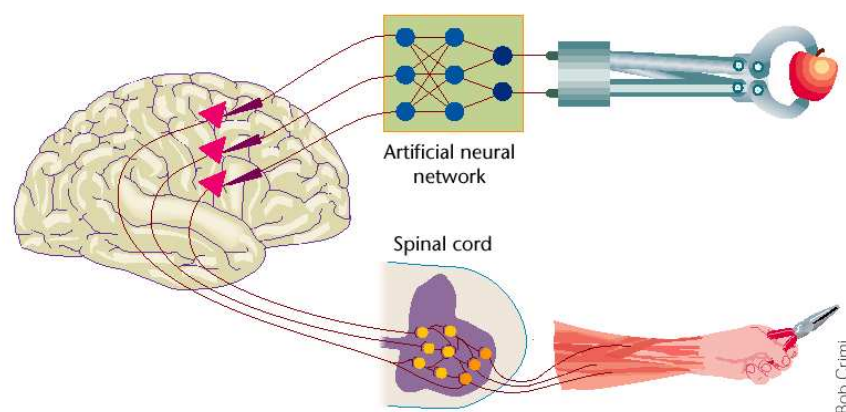


Fig. 1. Cortical neurons controlling voluntary arm movement could provide signals used to control a prosthetic arm. Large pyramidal neurons in motor cortex (red triangles) send axons to spinal cord, ending on interneurons and motoneurons. Motoneurons project to and contract arm muscles. Microelectrodes could record neural activity, which is transformed by an artificial neural network into signals required to operate a prosthetic arm.

Fetz. *Nature Neuroscience*. 1999: 2(7)