Source Extraction Representing Thumb and Little Finger Cortical Networks and Intra-Hand-Area Evoked Synchrony

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Abstract. A novel cerebral source extraction method is proposed (Functional Source Separation, FSS) starting from extra-cephalic magnetoencephalographic (MEG) signals in humans, based on source functional reactivity to the external stimulation. Their activity is obtained all along the rest state and during processing of a simple separate sensory stimuli of thumb or little finger. This method provides cerebral sources describing thumb and little finger primary representations, as demonstrated by their higher responsiveness to the corresponding finger stimuli and their different positions consistent with the homuncular organization. A dynamical index describing intra-regional synchrony was introduced, which showed higher levels when stimulating the thumb with respect to little finger stimulation, selectively in the gamma band ([33, 44]Hz). This indicates that the stimulation of a functionally prevalent finger (thumb) activates a cortical network more synchronized in the gamma band than a non-prevalent one (little finger).

1 Introduction

1.1 Synchronization phenomena

Brain processes mainly rely on changes in the synchronization of the recruited neuronal firing (functional binding and unbinding, [5]). Not only the synchronization among cerebral regions processing different stimuli features involving quite distant cortical areas are mandatory, but also the synchronization within a restricted cortical area.

Starting from extra-cephalic data, direct signals from recording channels are often used: if synchronization across distant areas is studied, this method is quite reliable,

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but in the present study the limited region devoted to the hand control is under investigation. In this case all channels are significantly sensitive to the activity from the same neuronal pools. For this reason, it is mandatory to achieve synchronization indexes between neuronal source activities instead of between channel signals.

To extract cerebral sources starting from the recorded magnetic fields, the MEG community main approach is to solve the so called 'inverse problem' [4], which identifies cerebral currents on the base of their spatial positions. In our region of interest, the neural networks are highly interconnected and superimposed (for a review see [12]) pulling the 'inverse problem' to its spatial resolution boundaries. Moreover, it implies to fix the source model, which suitability changes across different steps of the cerebral processing, and this limits the analysis when a neuronal group is followed from the rest state to task involvement. For this reason, blind source separation methods (BSS, Comon 1994; [1]) could be more suitable, discriminating different sources on the base of their generated signal statistical properties.

In particular, an ad hoc BSS algorithm was implemented, based on a priori information about sources functional properties. Once obtained single fingers cortical representation sources, a dynamic synchrony index was defined, related to the cortical network including both finger representations. This intra-regional index was studied when stimulating each finger separately.

2 Methods

2.1 Experimental Paradigm

Magnetoencephalographic (MEG) data were recorded from 15 healthy volunteers (mean age 31±2 years, 7 females and 8 males) during separate electrical stimulation of their right thumb or little finger. Ring electrodes were used to deliver around 300 stimuli with standard features (0.2-ms-long electric pulses, 631 ms inter-stimulus interval, stimulus intensities set at about twice the subject's sensory threshold, [9], Tecchio et al 1997).

A 28-channel MEG system (developed by our own group, Tecchio et al, 1997) operating in a magnetically shielded room (Vacuumschmeltze GMBH) was used, the active channels being regularly distributed on a spherical surface (13.5 cm of curvature radius) and covering a total area of about 180 cm^2. Brain magnetic fields were recorded from the left rolandic region, i.e. contralaterally to the stimulation, after positioning the central sensor of the MEG apparatus over the C3 site of the International 10–20 electroencephalographic system. The noise spectral density of each magnetic sensor was 5–7 fT/√Hz at 1 Hz. Data were analogically bandpass filtered through a [0.16–250] Hz and gathered at 1000 Hz sampling rate.

2.2 Functional source separation (FSS)

Some of the authors (Valente et al submitted) have developed a modified Independent Component Analysis (ICA) procedure, that explicitly uses additional information to bias the decomposition algorithm towards solutions that satisfy physiological assumptions, instead of extracting sources only on the base of their signals statistical independence. The method is based on optimizing a modified contrast function:

$$F = J + \lambda H \tag{1}$$

where J is any function as normally used for ICA, while H accounts for the prior information we have on sources. Parameter λ is used to weigh the two parts of the contrast function. If λ is set to zero, maximization of F leads to pure independence.
The optimization is performed by simulated annealing, so that function H can have any form (e.g. it does not need to be differentiable).

To identify neural networks devoted to individual finger central representation, the sources 'reactivity' to the stimuli was taken into account. This was defined as follows: the evoked activity (EA) was computed separately for the two sensorial stimulations, by averaging signal epochs centered on the corresponding stimulus (EA_T, thumb; EA_L, little finger) and subtracting the mean of the values in the 'no response' baseline interval [-30.-10] ms, t=0 corresponding to the stimulus arrival.

The reactivity coefficient (R) was computed as:

$$R_X = \sum_{t=20}^{40} \left|\mathrm{EA}_X(t)\right| - \sum_{t=-30}^{-10} \left|\mathrm{EA}_X(t)\right| \tag{2}$$

with X = T, L. The time interval ranging from 20 to 40 ms includes the maximum activation.

The constraint function H_X is then chosen as:

$$H_X = \varphi(R_X, k),$$

where

$$\varphi(R_X) = \begin{cases} R_X/k & \text{when } R_X \le k \\ 1 & \text{else} \end{cases} \tag{3}$$

and k is a suitable parameter quantifying the required response

The shape of function φ is such that the constraint is inactive when response is greater than k, so as to define an admissible region where the optimization is only driven by J. Parameter λ is chosen large enough H_X dominates the search. Therefore, a constrained optimization procedure is obtained.

To obtain the time behavior of the neural networks devoted to different finger cortical representations during different activation states, each functional source was extracted using data recorded during the two fingers separate stimulation.

To separate contributions representing individual fingers, we extracted a single component by using the constraint H_T, obtaining the functional source describing the time evolution of the thumb cortical representation (FS_T). Then, the procedure was repeated using H_L to obtain FS_L.

2.3 Functional source characteristics

Functional source evoked activities. To demonstrate that the extracted functional sources are more responsive to the stimulation of the district they represent, each source was observed when stimulating both the fingers. In particular the above defined indexes R_T and R_L describing respectively the responsiveness when stimulating thumb and little finger, were calculated for each of the two functional sources FS_T and FS_L.

Functional source localizations. To describe spatial characteristics of the sources FS_L and FS_T, they were separately retro-projected. To be noted that when a single component is retro-projected, as in our case, the field distribution is time independent, up to the scaling factor FS_X (t); this means that the localization algorithm produces fixed positions and directions along time, and only the source strength varies with time proportionally to FS_X (t). As localization procedure a moving Equivalent Current Dipole (ECD) model inside an homogeneous best-fitted sphere was applied. The ECD characteristics (explained variance = e.v.; spatial position) were calculated for each functional source. ECD coordinates, if e.v. > 85%, were expressed in a right-handed Cartesian coordinate system defined on the basis of three anatomical landmarks.

For comparison, the positions of the known markers of signal arrival in the primary sensory cortex, occurring at around 20 ms from the stimulus (M20), were calculated by standard procedure (Tecchio et al 1997, 2002) of averaging original channel signals.

2.4 Dynamic intra-regional synchrony index

The intra-regional synchrony index was obtained by the following 4 steps and examined in the two different conditions of thumb and little finger stimulations.

1) The $FS_T(t)$ and $FS_L(t)$ signals were forward-backward band pass filtered in the classical alpha (α= [7, 13]Hz), beta (β = [14, 32]Hz) and gamma (γ= [33, 44]Hz) bands (FS_X^b (t), where X = T, L; b = α, β, γ) by a Butterworth filter of the second order;
2) the FS_X^b (t) analytic signals were calculated, defined as:

$$a_X^b(t) = FS_X^b(t) + ih_X^b(t) \tag{4}$$

where $h_X^b(t)$ is the FS_X^b (t) Hilbert transform;
3) the module of the two analytical signals in each band were calculated and averaged across all stimuli epochs separately as:

$$|\, a_X^b(t)\,|_{aveX} = \frac{1}{N_X}\sum_{k=1}^{N_X} |\, a_X^b(t_k)\,| \tag{5}$$

where $t_k \in [T_1, T_2]$, with T_2-T_1 the intervals length and N_X is the number of considered stimuli for each finger X = {T, L} and *aveX* indicates that the averaged is performed for each analytical signal across T and L finger stimuli separately.
4) the indexes calculated at steps (3) were finally averaged across the two sources, obtaining a whole region of interest dynamic synchronization index ($Syn^b(t)$; it was estimated during both fingers separate stimulation. In par-

ticular the maximal value following each stimulation (Syn_M^b) was chosen to compare synchronization levels during thumb and little finger stimulations, in the 3 frequency bands.

3 Results

3.1 Functional extracted source characteristics

Functional source evoked activities. The activity of the source representing a finger, is compared when stimulating the finger itself with respect to when an other finger is stimulated. To do this, the defined indexes R_T and R_L, describing respectively the responsiveness to thumb and little finger stimulations, were both considered for each of the two functional sources FS_L and FS_T . The evoked activity of the two extracted sources, resulted significantly higher when the finger that source represents was stimulated (Table 1, $R_T > R_L$ for S_T, $p < .001$; $R_L > R_T$ for S_L, $p < .001$).

Table 1. Average and s.d. across subjects of FS_T and FS_L characteristics: spatial position (x-axis passing through the two preauricolar points directed rightward, positive y-axis passing through the nasion, positive z-axis consequently) with their explained variance (e.v.); the evoked activity indexes (R_T and R_L). Mean $M20_T$ and $M20_L$ positions are reported with their mean latency (lat) .

FSS	lat (ms)	e.v.	x (mm)	y (mm)	z (mm)	R_T	R_L
FS_T		0.97±0.04	-38±11	10±13	89±10	13.4±4.8	6.2±5.2
FS_L		0.95±0.07	-34±11	6±12	99±14	7.4±5.6	12.6±4.9
$M20_T$	24±2	0.96±0.18	-42±8	11±11	91±10		
$M20_L$	24±2	0.94±0.06	-33±10	6±13	100±10		

Functional source localization. Dipole coordinates (x,y,z) were computed for the two sources FS_T and FS_L in our 15 subjects group.

A General Linear Model (GLM) for repeated measures was estimated to test differences in source localization: as dependent variables the 3-dimensional coordinates vectors obtained for each subject were used, with the two levels *Finger* (Thumb, Little) as within-subjects factor. Factor *Finger* resulted significant ($F(3,12)=8.675$, $=0.001$, Table 1), corresponding to FS_T position significantly lateral, anterior and lower with respect to FS_L one. This was in agreement with M20 ECD positions when stimulating respectively thumb and little finger evaluated in same subjects (Table1).

3.2 Dynamic intra-regional synchronization index

The index Syn_M^b showed strongly different properties in the different bands following stimulation of the two fingers. In fact, in alpha and beta bands no effect was observed (paired t-test $p > .200$), while in gamma band the Syn_M^γ was significantly higher for the thumb stimulation than for the little finger (0.039 ± 0.020 and 0.026 ± 0.021 respectively, p=.013, fig. 1).

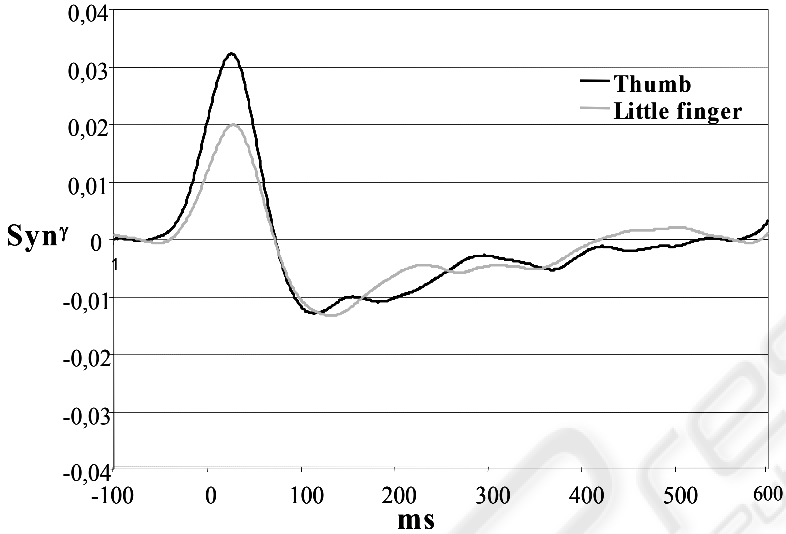

Fig. 1. Temporal dynamic of the synchronization index in the gamma band, being t=0 the sensory stimulus arrival on thumb (black) or little finger (grey).

4 Conclusion

The two functional extracted sources related to thumb (FS_T) and little finger (FS_L) cortical representations, resulted significantly different both with respect to their spatial positions and their activation properties. In fact FS_T position was significantly lateral, anterior and lower with respect to FS_L one, as physiologically expected. This positioning of the hand sensory representation boundaries completely agrees with the classical homuncular somatotopy [10] [15], as also recently confirmed by other techniques (e.g. functional Magnetic Resonance Imaging, [7], optical imaging, [14]).

The thumb cortical representation showed strongly higher activity evoked by thumb than little finger stimulation and the same selective properties showed the little finger cortical representation. This strengthens that extracted sources are significantly different and suitable representing cortical networks specifically connected to different fingers.

Using these functional extracted sources activities, an intra-regional synchronization index was introduced. In particular it resulted finger-dependent in the gamma band [5] [6], whereas in beta and alpha bands the synchronization index was similar for thumb and little finger stimulations. Oscillatory activity within alpha and beta frequency bands is well known to react to sensorimotor tasks in the whole rolandic region [11]; the gamma band is instead characteristic of focal network activations [3].

Gamma band is moreover indicated with increasing evidences as playing a pivotal role in perceptive [8] and cognitive motor tasks [13]. Present result, of gamma band synchronization higher following stimulation of the thumb than of the little finger, will suggest a new phenomenon: taking into account that thumb is functionally prevalent with respect to little finger, it could be hypothesized that the synchronization in the gamma band codes for functional prevalence in the sensory hand representation, strengthening previous results of our group [16].

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