Studying Brain Visuo-Tactile Integration through Cross-Spectral Analysis of Human MEG Recordings

S. Erla[1,2], C. Papadelis[1], L. Faes[2], C. Braun[1], and G. Nollo[2]

[1] Laboratory of Functional Neuroimaging, Center for Mind/Brain Sciences (CIMeC), University of Trento, Italy
[2] Biophysics and Biosignals Lab, Department of Physics (BIOtech), University of Trento, Italy

Abstract— **An important aim in cognitive neuroscience is to identify the networks connecting different brain areas and their role in executing complex tasks. In this study, visuo-tactile tasks were employed to assess the functional correlation underlying the cooperation process between visual and tactile regions. MEG data were recorded from eight healthy subjects while performing a visual, a tactile, and a visuo-tactile task. To define regions of interest (ROIs), event-related fields (ERFs) were estimated from MEG data related to visual and tactile areas. The ten channels with the highest increase in ERF variance, moving from rest to task, were selected. Cross-spectral analysis was then performed to assess potential changes in the activity of the involved regions and quantify the coupling between visual and tactile ROIs. A significant decrease ($p<0.01$) in the power spectrum was observed during performing the visuo-tactile task compared to rest, both in alpha and beta bands, reflecting the activation of both visual and tactile areas during the execution of the corresponding tasks. Compared to rest, the coherence between visual and tactile ROIs increased during the visuo-tactile task. These observations seem to support the binding theory assuming that the integration of spatially distributed information into a coherent percept is based on transiently formed synchronized functional networks.**

Keywords— **MEG, ERFs, Power, Coherence, Visuo-Tactile.**

I. INTRODUCTION

In everyday life, it is common to perceive visual and tactile stimuli at the same time or to perform tasks requiring integration of visual and haptic information. One of the main goals of neuroscience is to identify brain networks connecting different brain areas and their role in executing complex tasks. Recent advancements enhanced our understanding of multisensory integration process that was shown to take place in midbrain, thalamus and cortex [1]. The combination of information from different sensory cues in these areas often seems to enhance the neural activity in comparison to the activity caused by the respective pure stimuli. This is also expected for the visuo-tactile integration process. Many studies have already investigated this topic, focusing mostly on tactile texture perception [2] since it is crucial for both healthy as well as blind subjects [3]. However, a clear neurophysiological explanation of the interaction between visual and tactile sensory systems is still unclear.

The present study was undertaken in order to explore large-scale integration of visual and tactile processes in the cortex through analyzing the coupling relations of cortical activity recorded simultaneously from visual and somatosensory areas.

II. MATERIALS AND METHODS

A. *Experimental Protocol and Data Acquisition*

Neurophysiological brain signals were recorded from eight healthy subjects during performing three different tasks. During the first task, namely visual block (V), participants were asked to fixate on the center of a white screen showing a geometric pattern consisted of many black dots (Fig 1a). The visual stimuli resembled letters of the Braille code developed for helping blind people. Subjects had to identify if the orthogonal segment was turned to the left or to the right side. During the tactile session (T), subjects had to touch a tablet with the same geometric pattern as this appeared on the screen during the previous session. No visual stimuli were provided at this time. The subjects' task was again to identify the direction of the pattern's orthogonal segment (Fig 1a). During the visuo-tactile block (VT), both visual and tactile stimuli were provided to the subjects. They had to identify if the two patterns were identical or not (Fig 1a).

MEG signals were recorded (VSM System, 275 gradiometers) in two time intervals of one second (w0 and w1), starting one second before the stimulus, as described in Fig. 1b. Each block was repeated 40 times (trials).

B. *Preprocessing and ROIs Selection*

The acquired signals were FFT band-pass filtered (2-45 Hz), downsampled from 586 to 293 Hz, and normalized (zero-mean).

In order to focus on the relevant information, a reduced number of scalp recordings was considered for further analysis. Two wide regions (Fig. 2c), corresponding to the

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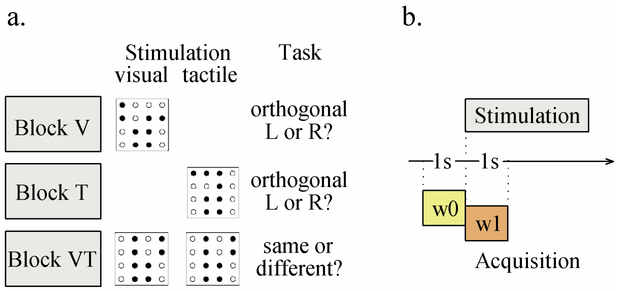

Fig. 1 (a) Schematic diagram of the experimental protocol. Three block sessions were totally performed (b) Time course of data acquisition

somatosensory and the visual cortex, were identified. Then, event-related fields (ERFs) were estimated from MEG data related to these two areas. For each subject, rest ERF variance was calculated on the whole w0 window. Differently, task ERF variance was computed considering the typical time intervals of visual and somatosensory ERFs (70-150 ms and 25-70 ms after stimulus respectively). The ten channels with the highest increase in ERF variance moving from rest to task were selected both for somatosensory and visual regions of interest (ROIs).

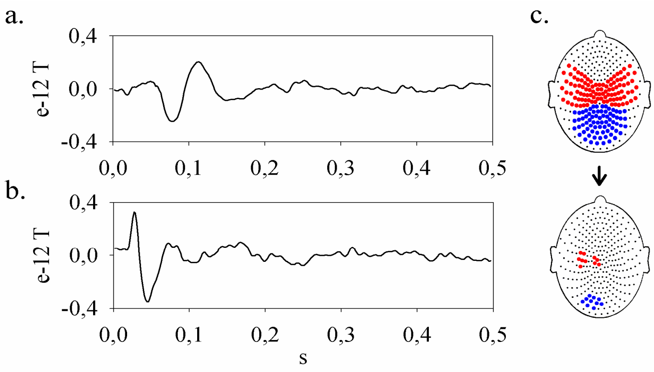

Fig. 2 Event-Related Fields (ERFs) after stimulus, for visual (a) and somatosensory (b) brain areas in one representative subject. Maps of the visual (blue) and somatosensory (red) considered wide regions and of the ten channels with the higher increase in signal variance moving from rest to task (ROIs) for this participant (c)

C. *Cross-Spectral Analysis*

For each subject and experimental condition, the preprocessed signals belonging to the two selected ROIs were collected into the $M \times N$ data matrix $\mathbf{Y}=\{y_m(n)\}$, $n=1,\ldots N$, $m=1,\ldots M$ ($M=20$ signals, $N=293$ samples) and then described by a multivariate autoregressive model as:

$$\mathbf{Y}(n)=\sum_{k=1}^{p}\mathbf{A}(k)\mathbf{Y}(n-k)+\mathbf{U}(n) \tag{1}$$

where p is the model order, $\mathbf{A}(k)$ are $M \times M$ matrices describing the linear interaction at lag k from $y_j(n-k)$ to $y_i(n)$, and $\mathbf{U}(n)=[u_1(n),\ldots,u_M(n)]^{\mathrm{T}}$ is a vector of zero-mean uncorrelated white noises with diagonal covariance matrix $\mathbf{\Sigma}$. Estimation of the model coefficients, with fixed order $p=9$, was performed through standard vector least squares identification.

Multivariate spectral analysis was performed transforming (1) in the frequency domain to yield $\mathbf{Y}(f)=\mathbf{H}(f)\mathbf{U}(f)$, where $\mathbf{Y}(f)$ and $\mathbf{U}(f)$ are the Fourier Transform of $\mathbf{Y}(n)$ and $\mathbf{U}(n)$, and the transfer matrix $\mathbf{H}(f)$ was obtained as the inverse of the frequency domain coefficient matrix $\overline{\mathbf{A}}(f)=\mathbf{I}-\sum_{k=1}^{p}\mathbf{A}(k)e^{-i2\pi fkT}$. Then, the spectral matrix was obtained as $\mathbf{S}(f)=\mathbf{H}(f)\mathbf{\Sigma}\mathbf{H}^{\mathrm{H}}(f)$. The diagonal elements of $\mathbf{S}(f)$, $S_{ii}(f)$, are the power spectral densities of each modeled signal y_i. Multivariate spectral decomposition [4] was applied to each spectrum S_{ii} to find the partial spectra $S_{ii}(\alpha)$ and $S_{ii}(\beta)$ related to the poles of the process with frequency inside the alpha (8-13 Hz) and beta (13-30 Hz) frequency bands; the area underlying each partial spectra was then taken as a measure of the power within the two bands, $\overline{P}_\alpha$ and $\overline{P}_\beta$. The off-diagonal elements of $\mathbf{S}(f)$ were used to measure in the frequency domain the linear coupling between each pair of signals y_i and y_j through the squared coherence function:

$$C_{ij}^2(f)=\frac{\left|S_{ij}(f)\right|^2}{S_{ii}(f)S_{jj}(f)} \tag{2}$$

D. *Statistical Analysis*

Forty values (corresponding to the 40 trials) of alpha and beta power were obtained for each sensor of the two selected ROIs during rest, V, T and VT tasks in each subject. Statistical analysis was performed separately for each subject with the following scheme. Two-way ANOVA was performed to assess the significance of differences due to scalp-position (somatosensory or visual cortex) and to stimulus-type (no stimulus, V, T, VT). When the ANOVA test yielded a significant p value ($p<0.05$) for both considered factors, post-hoc multiple paired Wilcoxon tests, with Holm correction for multiple comparisons [5], were performed to assess differences between pairs of power values. The number of significant changes across subjects was considered to analyze population tendencies.

In a second step, for each subject, 40 coherence values (one for each trial) were calculated averaging the estimated coherence within the alpha and in the beta frequency bands (8-13 Hz and 13-30 Hz respectively). For each participant, trial and frequency band, the average coherence value between each visual channel and all the somatosensory channels was considered as representative for the coupling relation between the visual channel and the whole somatosensory ROI. Repeating this computation for all the ten visual channels, ten measures of coherence between the two areas were obtained for each trial. In each subject, multiple Wilcoxon T-tests were performed to assess the significance of differences between the calculated coherence values in rest, V, T and VT conditions. Again, the number of significant changes across subjects was considered as an index of population tendencies.

III. RESULTS

In Fig. 3, results of cross-spectral analysis performed for one representative subject are shown. In the first column, power spectral density plots are presented for one channel located above the visual cortex during the execution of V, T, and VT tasks. In the second column, the same is shown for one channel representing the somatosensory cortex. In respect to rest, during V task, the power content was lower in both alpha and beta frequency bands in the occipital area, but it did not show evident differences in the somatosensory area. During the T task, rhythmic oscillation at alpha and beta bands showed amplitude decrease for the somatosensory channels. Finally, during VT task alpha and beta power decreased both in occipital and somatosensory areas, thus suggesting the activation of both brain areas while executing the combined task. Coherence spectra, estimated between the two channels belonging to occipital and somatosensory area, are shown in the last column of Fig. 3.

Coherence was lower during the V task in both frequency bands, whereas it was unchanged in the alpha and increased in the beta band during the T task. Finally, coherence was higher in both frequency bands during the combined task. These trends suggest that only when the two tasks were performed contemporaneously an increase of coupling between the two areas could be observed.

In Fig. 4, values averaged over trials for the same subject are shown. The power content of alpha (Fig. 4a) and beta (Fig. 4b) was significantly lower during task in comparison with rest, indicating brain activation, during V in the occipital cortex, during T in the somatosensory areas and during VT in both areas. In the beta band, a significant power decrease was also noted in the occipital area during T.

In Figs. 4c and 4d coherence results are presented. The coherence increased significantly in both frequency bands during VT and only in the beta band during T.

Figs. 5a and 5b show the percentage of subjects in which a significant change in the power spectra values was revealed in alpha and beta frequency bands respectively. In the alpha band, a significant power decrease was found in more than 50% of the subjects during V in the occipital cortex, during T in the somatosensory areas and during VT in both considered brain regions. A significant decrease was present in a larger number of subjects in the same brain locations and stimulation conditions in the beta band. Fig. 5c evidences a larger percentage of subjects where the coherence increased during VT, but not during V and T, in the alpha band. The same result was obtained in the beta band. Moreover, in this frequency band more than 50% of the subjects showed increased coherence also during T.

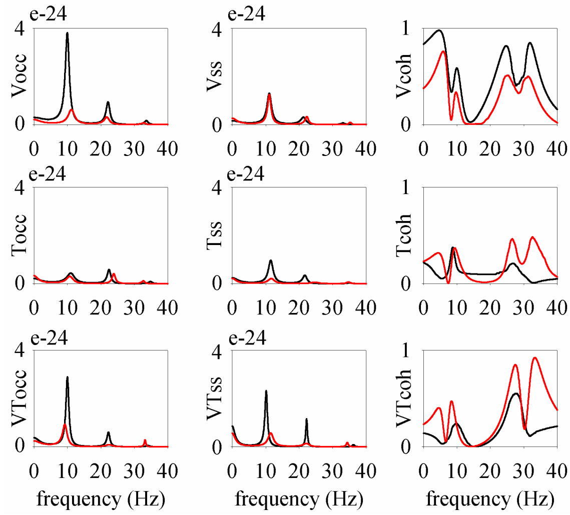

Fig. 3 Cross-spectral analysis on a representative subject for one channel located above the visual cortex (occ, first column) and for one channel representing the somatosensory cortex (ss, second column). Coherence spectra between the two channels (coh, third column). All this results are shown for the V (first row), the T (second row) and the VT (third row) task, during rest (black) and during performing the task (red)

IV. DISCUSSION

The accordance in time and space of different sensory inputs is nowadays considered to promote multisensory integration [6]. In this study, this process is evoked by a task in which healthy subjects perceived visual and tactile stimuli simultaneously provided to the subjects. Two control conditions were also considered (pure-visual and pure-tactile task) in order to distinguish the processes which are involved or not in the multisensory integration.

Cross-spectral analysis was performed in the two sensory ROIs in order to (i) evidence changes in the rhythmic oscillations of the involved regions due to activation and (ii) quantify the coupling between visual and tactile ROIs.

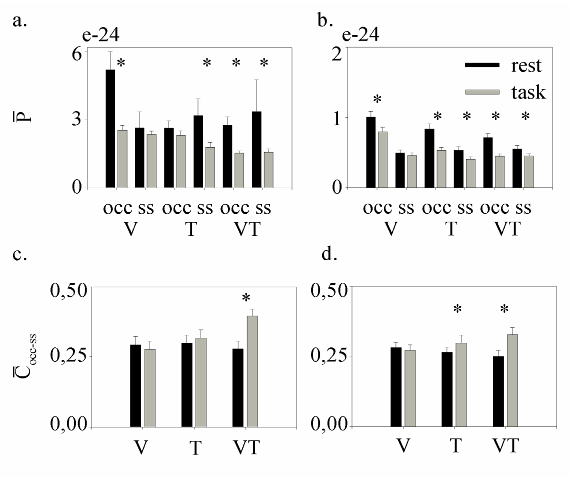

Fig. 4 Mean (± SE) alpha power (a), beta power (b), alpha coherence (c) and beta coherence (d) results in one representative subject for visual cortex (occ) and somatosensory cortex (ss) for the V, the T and the VT task, during rest (black) and task (grey). * significant (multiple testing)

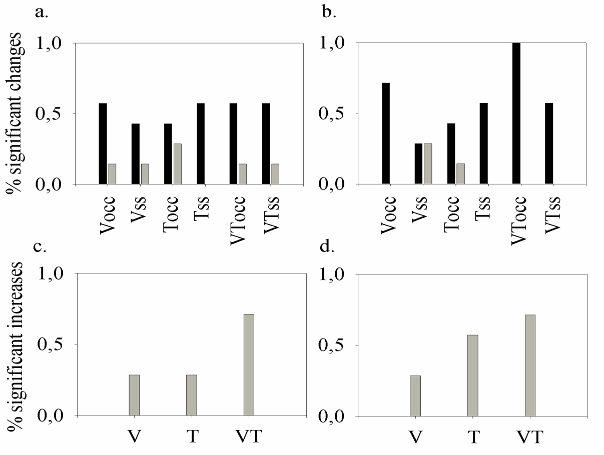

Fig. 5 Population significance considerations. Percent of subjects for which decrease (black) or increase (grey) in alpha (a) or beta (b) power was significant as a relation to the performed task (V, T, VT) and brain area (occ, ss). Percentual number of subjects for which increase in coherence was significant as a relation to the performed task (V, T, VT)

While executing the pure-visual task, subjects showed a decreased power in both alpha and beta frequency bands in the occipital area, but not in the somatosensory area. On the contrary, pure-tactile task induced activation (power decrease) only in the somatosensory region. Finally, the execution of a combined VT task suggested activation of both brain areas. These results indicated the neuronal network activation during task performance engaging different sensory regions and confirmed the ability of the considered spectral estimator to reveal it.

Coherence results showed no significant changes during pure-visual and pure-tactile tasks. On the contrary, coherence increased significantly in the most of the subjects during the combined task in both frequency bands. This result suggested the tendency, at least in our small population sample, to enhance the coupling between visual and somatosensory cortex during tasks involving both areas at the same time.

V. CONCLUSIONS

The proposed visual tactile task seems able to elicit multisensory integration process that are quantifiable by cross-spectral analysis of MEG recordings in healthy volunteers. These findings bring evidence supporting the binding theory, that describes the integration of spatially distributed information into a coherent percept as due to transiently synchronized functional networks [7,8,9].

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Author: Erla Silvia

Institute: CIMeC and BIOtech, University of Trento
Street: Via delle Regole 101, Mattarello
City: Trento
Country: Italy
Email: silvia.erla@email.unitn.it