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Multimodal analysis of a sustained attention protocol: Continuous Performance Test assessed with Near Infrared Spectroscopy and EEG

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Abstract—**The aim of this work is to describe, using functional imaging techniques, the spatial and temporal distribution of neural activations ensuing from execution of cognitive functions and to find correlation in data coming from analysis modalities related to different physical properties. A 10-min continuous performance test (CPT) was administered to a group of healthy subjects as measure of sustained attention. Images of Electroencephalography (EEG) and of Near Infrared Spectroscopy (NIRS) were recorded during the task. Cerebral activation's measure is obtained from the recording of quantities linked with electrical neural activity for the EEG and with change in blood oxygenation for the NIRS system. Good agreement was found between the two modalities, both showing higher activation in the middle upper frontal region and similar temporal trend. A further understanding of the superior central nervous system behavior can be achieved from combined use of both imaging modalities.**

I. Introduction

Electroencephalography is the neurophysiologic measure of the electrical activity of the brain by recording from electrodes placed on the scalp. Due to its high temporal resolution (milliseconds) this technique is adapt to describe quick changes typical of the electrical scalp potentials. Functional near-infrared (fNIR) spectroscopy, instead, uses specific wavelengths of light, injected at the scalp, to measure noninvasively changes in the concentrations of oxy- and deoxy-hemoglobin (oxy-Hb and deoxy-Hb) during task-related brain activity [1]-[2]. Most biological tissues are relatively transparent to near-infrared light (700-900 nm). In this optical window the absorption due to oxy-Hb and deoxy-Hb is higher than that of water, so fNIR uses specified wavelengths in the optical window. Introduced photons are absorbed and scattered in a relatively predictable pattern, so changes in photon absorption by oxy- and deoxy-Hb are measured by photodetectors placed on the surface of the skin. Variations in light absorption are converted into variations in the relative quantities of oxy- and deoxy-Hb in the underlying capillary bed, which provide information about the neural activity in the cortex. Hence, fNIR spectroscopy is a safe functional neuroimaging modality and, also, offers a good spatial resolution.

In the last years, one of the most important areas of research in the field of cognitive neuroscience was the attentional system. In Posner and Petersen's study [3], based on electrophysiological and metabolic investigations, three fundamental systems involved in attentive processes' organization are described: Posterior Attentional System (PAS), Anterior Attentional System (AAS), and vigilance attentional system. Attention is defined as the ability to react to stimuli which are administered to the subject; the capability of maintain an high vigilance level for a long time, allowing the subject to respond against presentation of infrequent stimuli, is called Sustained Attention. This is an important cognitive function in human behavior, having influence on other attentional aspects (selective attention, divided attention) and superior function (memory, learning). Task of sustained attention lead to the activation of AAS [4], showing mostly involvement of frontal, prefrontal, parietal and supplementary motor areas [5]. An attentive task long used in assessing cognitive performance, related or not to some measuring processes is the continuous performance test CPT [6].

II. Materials and Methods

A. CPT Task

The present study is based on the "not-X" CPT task, often called the Conners' CPT. The subjects were seated on a comfortable chair. A computer screen was placed at a distance of 60 cm in front of their eyes. The experiment consisted of showing 26 different letters, of the English alphabet, which were presented sequentially in random order on the computer screen. The letters appeared black on a white background; they were 7.5 cm high and 7 cm wide,

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resulting in a visual angle of 7°. Subjects were instructed to press the mouse button with the index finger of their right hand as fast as possible when occurred any letter other than X, and to inhibit the response when occurred the X. The presentation time of each stimulus was 250 ms with an inter-stimulus interval of 2000 ms or 1000 ms. The experiment involved 450 stimuli, 25 letters X (NoGo stimulus) and 425 other letters (Go stimulus). Duration of testing was approximately 10 minutes.

B. EEG Recordings

The EEG was recorded with 19 Ag/AgCl electrodes placed according to the international 10/20 system (Fp1/Fp2, F3/F4, F7/F8, T3/T4, C3/C4, T5/T6, P3/P4, O1/O2, Fz/Cz/Pz). A1 and A2 were used as reference . Two bipolar additional electrodes were used for registration of eye movements (EOG): one was placed at the outer canthi and one was placed below the right eye. For recording we used a 32-channel AC/DC-amplifier (Neuroscan) and a data acquisition software (Scan, version 4.3). The hardware filter was set to a bandpass that ranged from 1 to 70 Hz and was used a notch filter at 50 Hz. The A/D rate was 500 Hz. All electrode impedances were less than 5kOhm.
For later analysis of the event-related potentials, a specific marker was recorded in a separate file for each condition of the CPT.

C. fNIR Recordings

The fNIR device used for this study was provided by Drexel University (Philadelphia, PA) and includes a flexible sensor that covers the forehead, a control box for data acquisition and a computer for data analysis. The sensor consists of 4 LED light sources and 10 photodetectors, giving 16 acquisition channels (Fig.1).

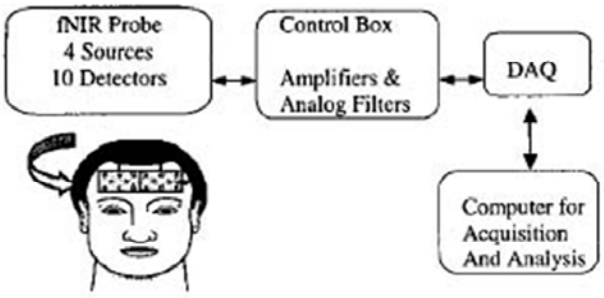

Fig. 1: fNIRS system

Changes in light absorption are then converted in measure of changes of oxy-Hb, deoxy-Hb and blood volume (BV) using the Modified Beer-Lambert Law. The used acquisition frequency is 2 Hz, as the hemodynamic response evolves in seconds.

D. Subjects

Nine healthy volunteers took part in the fMRI acquisition, whereas NIRS acquisitions were available only for seven of them. Mean age was 24 years (SD 2.9 years) and all subjects were self-reported right handed. None of the subjects had a life time or family history of neurological or psychiatric illness and none received any psychotropic drug.
Written informed consent was obtained from all volunteers after the examination and test procedure had been explained. The study was approved by the ethical review board of the "E. Medea" institute.

E. Data analysis

After the artifact rejection with the Independent Component Analysis (ICA) the continuous EEG was digitally low-pass filtered below 30 Hz and was segmented into epochs starting at 300 ms before the onset of the stimulus (baseline) until 700 ms after stimulus onset. A process of average of the epochs was then applied over a period time of 2 min (this allows the average of a sufficient number of events to make the process statistically relevant), in order to focus the study on the event-related potentials (ERPs). The electroencephalographic study was focused on the two ERP component mainly investigated in attention and response inhibition tasks: the N2 component and the P3 component [7], [8]. It has been demonstrated that performance level depending on sustained attention is not constant, but is likely to decrease with time, and that was the clearest index for sustained attention deficit [6]. The spatio-temporal mapping of the brain activity underlying a similar test would be of great interest in the field of functional neuroimaging.

For this reason fNIR measures have been combined with EEG measures. From fNIR measures, variations of oxy- and deoxy-Hb were obtained from the Modified Beer-Lambert Law [1]. Using a repeated measure ANOVA, data were analyzed for significant changes between the beginning and the end of the task and for possible differences in activated areas.

III. Results and Discussion

With regard to presentation of different stimuli, latencies and amplitudes considered indicative of attentive processes were calculated. As widely documented in literature, two ERP components are of interest in a CPT test: the N2 component and the P3 component. Cortical distribution of electric potentials is showed in Fig. 2: interpolating values of electrodes scalp maps are obtained. Temporal resolution, as explained above, was maintained in the range of two minutes. Nevertheless, this relatively poor temporal resolution makes possible the observation of potential distribution's variation during the test and is not in contrast with the temporal characteristic of attentional process (involving slow temporal dynamic). In this figure are shown maps corresponding to N2 (Fig.2 (a)) and P3 (fig.2 (b)) components. For the N2 component, important variations in amplitude and distribution were observed during the overall 10 min: initially, most activity is mainly in left frontal area, in the next tree blocks activity is located in centroparietal areas with an increase in amplitude, in the last block again there is a left lateralization. On the other hands, P3

component maintain spatial distribution more localized and stable, in center parietal area, slightly lateralized to the right, surrounding Fz electrode; differences are observed on amplitude: there is a trend to increase in the first three blocks, followed by a sudden decrease in the last two; in the very last block it is possible to see a slight anterior shift.

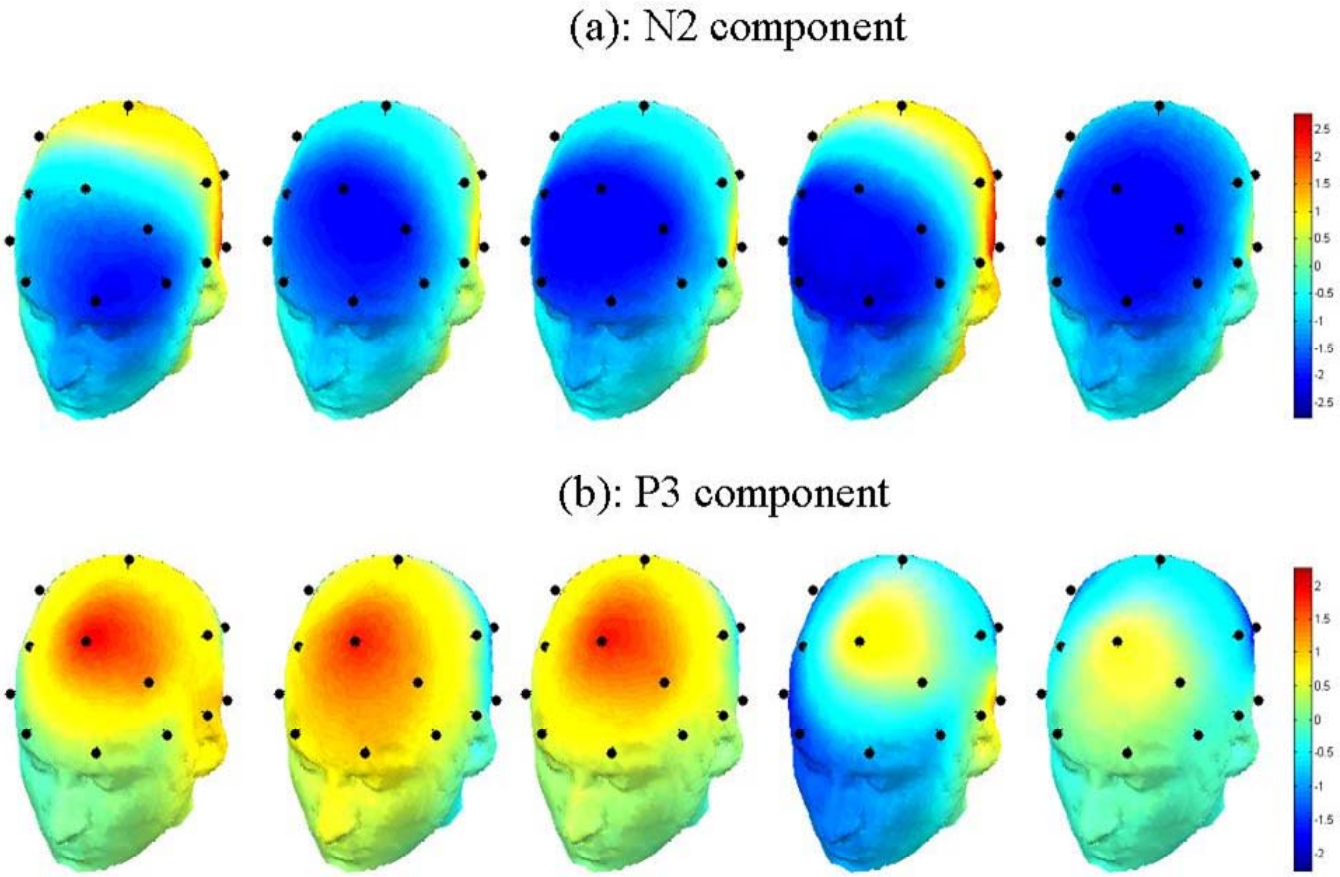

Fig. 2: Cortical distribution of electric potentials corresponding to N2 (a) and P3 (b) components in five different moments of the task. Each map refer to a 2 min interval time.

The fNIRs measures revealed significant differences between the beginning and the end of the task; temporal resolution was in the range of 2 minutes for consistency with the EEG analyses. Values for each subject in the two stages (beginning and end of the task) were normalized to the mean in the first stage. In particular, the oxygenation values increased significantly ($p<0.05$) from the initial to the ending stage of the task (Fig.3). Values for the deoxy-Hb, instead, revealed a significant decrease ($p<0.05$) (Fig.4).

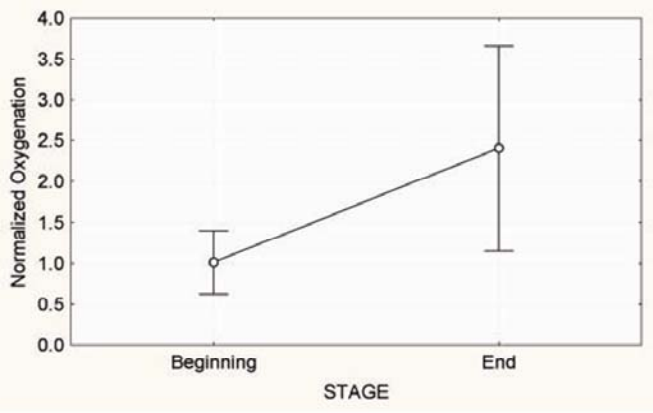

Fig. 3: Changes in mean oxygenation over time.

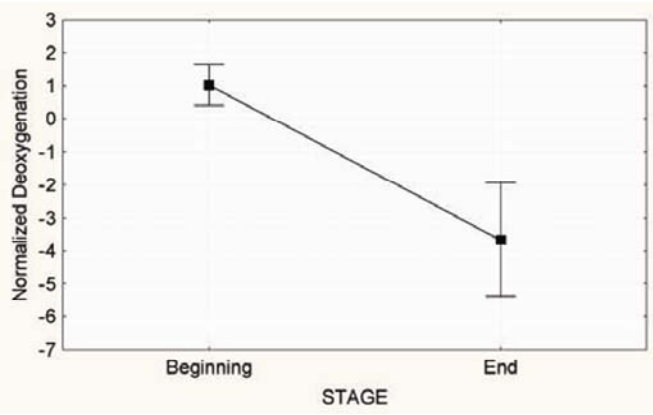

Fig. 4: Changes in mean deoxygenation over time.

Moreover, oxygenation values show the most important change between beginning and end of the task in the middle-right region. Fig. 5 shows the different temporal evolution of mean oxygenation values in different regions. Localization of oxygenation differences is allowed by the spatial resolution capabilities of the fNIR technology [9].

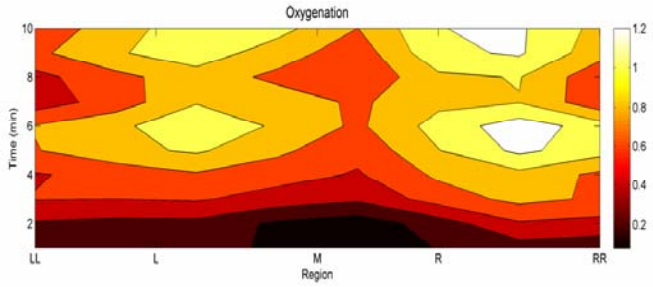

Fig. 5: Evolution during the task of mean oxygenation in different frontal regions (LL: extreme left; L: left; M: middle; R: right;, RR: extreme right).

IV. Conclusion

As expected, P3 component's amplitude in the examined group is increasing during the first task blocks because of the maintenance of a high attention level. Interesting confirmations to this interpretation are also produced by the results from fNIR measures, revealing increasing oxygenation during the task. This can be due to a progressive larger involvement of cerebral areas so that the requested task could be done in the best way, as it is confirmed from the good results showed from the CPT's performance index relative to this period.

Afterwards, on the contrary, the component's amplitude is reduced, side by side to a physiological decline of performances. This behavior might be interpreted as indicative of subject's attentive resource exhaustion, i.e. the subject can not keep the same level of attentiveness for a prolonged time period, otherwise it can be linked with the onset of automatism phenomena, less expensive for the subject but characterized by a higher degree of error. It is also noteworthy that the investigation of both P3 component and fNIR oxygenation measures reveals higher activation in the middle upper frontal region. Hence good agreement is seen between the two modalities, as fNIR measures the hemodynamic response consequent to the electrical activation recorded from EEG. A combined use of the two functional analysis, based on the agreement of these preliminary results, can be further explored in order to exploit all the possibilities offered by NIRS and EEG systems.

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