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Analysis of the dynamical behaviour of the EEG rhythms during a test of sustained attention

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Abstract—**In clinical routine, the evaluation of sustained attention is often performed analyzing behavioral data collected during specific tests. It is not common to match such analyses with a detailed examination of the subject's simultaneous electroencephalographic (EEG) activity, and particularly its frequency content. In this study, 9 healthy volunteers underwent a modified Conners' CPT test, while their EEG were contemporarily recorded. Spectral power was calculated for each of the recorded EEG signals, with particular attention to frequency bands that are traditionally reported in literature. Then Compressed Spectral Array (CSA) sequence of spectra was plotted, and the analysis of the variability of the rhythms was carried out. Evaluation of the obtained results shows that the nine subjects shared a progressive backshift of alpha rhythm during the accomplishment of the CPT test. Moreover, beta and gamma activities were stronger in the right than in the left hemisphere. An intense and widespread decrease in EEG spectral power during test performing became visible in many subjects. Statistical analysis provided evidence that EEG activity correlates with the test behavioral results in many cerebral areas. For this reason, we encourage further investigations of the combined employment of tests and EEG recording during the clinical assessment of sustained attention performance.**

I. Introduction

SUSTAINED ATTENTION is the skill of maintaining a high degree of vigilance on phasic events during a long period of time. Attentive system in humans is highly sensitive to time, and the attentive performance conceals a complex dynamic phenomenon. The investigation of the attentive performance during time is of utmost interest, under both a physiological and a clinical point of view. Sustained attention must not be confused with arousal: the latter tends to diminish in a quiet environment, or in a situation of prolonged performance, but its decrease is not necessarily connected with a decline in attentive performance.

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Previous imaging studies have demonstrated that activation of (frontal) Broadman's areas 9 and 11 and parietal cortical regions, mainly in the right emisphere, are connected with sustained attention performance [1].

Oscillations of cortical activity in beta and gamma frequency ranges (14 up to 80 Hz) seem to play an important role in the functional organization of neuronal activity that underlies cognitive processing and attentional performance [2].

Several studies reveal an enhancement of gamma activity in subjects who undergo attentive tests, principally during the early stages of the examination [3]. Electrophysiological studies show that synchronized gamma activity is connected with the capability of linking object features and situation details [4]. Moreover, tasks which require active involvement by the participant induce far more impressive gamma power responses.

Beta frequency band includes a wide range of cortical contributions: visual system activation, motion planning activity, *habituation* tonic decreases and other cortical phenomena merge in the most variable EEG "rhythm".

Klimesch suggests that synchronized alpha rhythms, when associated with mental inactivity (*idling condition*), can be crucial for the onset of strong inhibitory effect [5]. Mental *idling* implies that a wide cortical area, at least a few square centimetres large, must be cut off from the processing of sensory information.

Differently from alpha activity, signal power that falls in theta band is believed to belong to the coding of new information [6].

The aim of this study was to accurately investigate surface electroencephalographic activity during an inhibitory attentive test (Conners' CPT test) administration in a healthy population, and to identify time variations in its frequency content. Moreover, interest was set on integrating CPT's behavioural indexes with EEG data.

II. Materials and Methods

A. Conners' CPT task

The present study is based on the "not-X" CPT task, often called the Conners' CPT [7]. The test was performed in a dimly lit and quiet room. The subjects were seated on a comfortable chair. A computer screen was placed at a distance of 60 cm in front of their eyes. All the 26 different letters of the English alphabet were presented sequentially in random order on the screen. Letters appeared blackcoloured, on a white background; they were 7.5 cm high and 7 cm wide, 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 occurring any letter other than X, and to inhibit their response when occurring the X. The presentation time of each stimulus was 250 ms with a random inter-stimulus interval of 2000 ms or 1000 ms. The experiment involved 450 stimuli: 25 X letters (NoGo stimulus) and 425 other letters (Go stimulus). The total duration of the test was approximately 10 minutes.

B. EEG recordings

19-channel EEG was recorded with 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 additional bipolar electrodes were used for the collection of eye movements (EOG): one was placed at the outer canthi and the other one was below the right eye. All the EEG recordings were performed by means of a 32-channel AC/DC-amplifier (Neuroscan) and its data acquisition software (Scan, version 4.3). Raw data were low pass filtered (hardware anti-aliasing filter) at 70 Hz and notch filtered at 50 Hz. The A/D sampling rate was 500 Hz. Each electrode impedance was below 5kOhm.

C. Subjects

Nine healthy volunteers, comparable for age and school attendance participated in the experiment. All subjects were right-handed, with a mean age of 24 years (SD 2.9 years, range 18–28 years). All volunteers were native Italian speakers and were not paid to participate, 8 of the subjects were male and 1 was female. They all had normal vision and had no history of psychiatric disorders. The participants were screened thoroughly for neurological symptoms: none of them showed any neuropsychological illness; cognitive level and attentive capability were normal; none of them had any first-degree relatives with a psychiatric illness. 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.

D. Conners' CPT analysis

Traditional Conners' CPT analysis includes the computation of several indexes: omission errors, commission errors, reaction times and an *overall index* of subject's performance [10]. An omission error is committed anytime the subject does not respond to the non-target stimulus; a commission error is committed whenever he gives a response to a target stimulus. Mean reaction times are separately calculated for correct answers to non-target stimuli and for commission errors to target stimuli.

E. EEG analysis

1) Pre-processing

Firstly, EEG data were cleaned up from ocular artifacts by means of Independent Component Analysis (ICA) algorithm, and digitally filtered with a band pass filter (1-48 Hz). EEG signals were then downsampled at 100 Hz.

2) Frequency analysis

The frequency analysis of EEG was performed through an AR model in batch implementation. The model was applied on time windows of 3 sec length, running along the whole recording (10 min) with a 50% overlap. The Yule-Walker estimation procedure was used and the model order was chosen according to a whiteness criterion (Anderson's test). For each time window, an AR power spectral density (PSD) was obtained and a compressed spectral array (CSA) was plotted for each recording electrode. Fig. 1. shows an example of CSA obtained for subject n°6, lead F4 (right frontal area).

From each spectrum, the power related to the EEG rhythms (theta 4-8 Hz, alpha 8-13 Hz, beta 13-30 Hz and low gamma 30-45 Hz) was extracted through the spectral decomposition procedure described in [8]. Fig.2. shows the time course of the per cent variation (%) of the four EEG rhythms during the test.

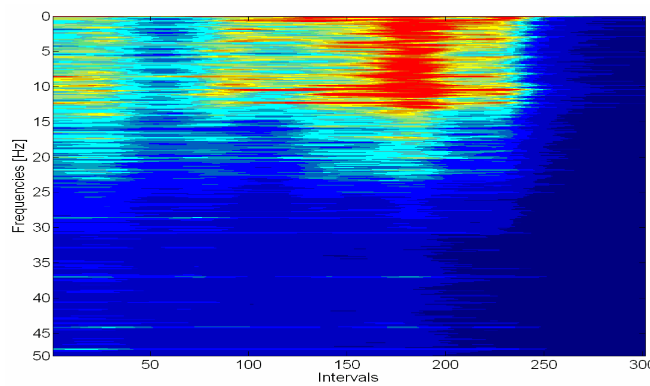

Fig. 1. EEG power distribution in time and frequency (compressed spectral array) for subject n°6, lead F4.

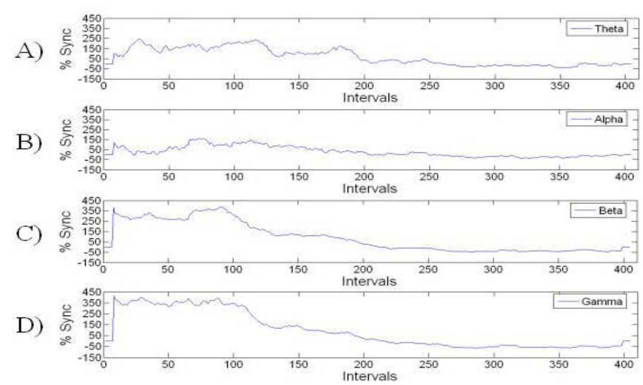

Fig. 2. Time course of the per cent variation (%) of the four EEG rhythms during the test (A: theta; B: alpha; C: beta; D:gamma).Subject n°6, lead F4.

3) Post- processing

In order to put into evidence variations in the EEG frequency content, with respect to the rest condition (measured before the beginning of the test), the rhythm synchronization

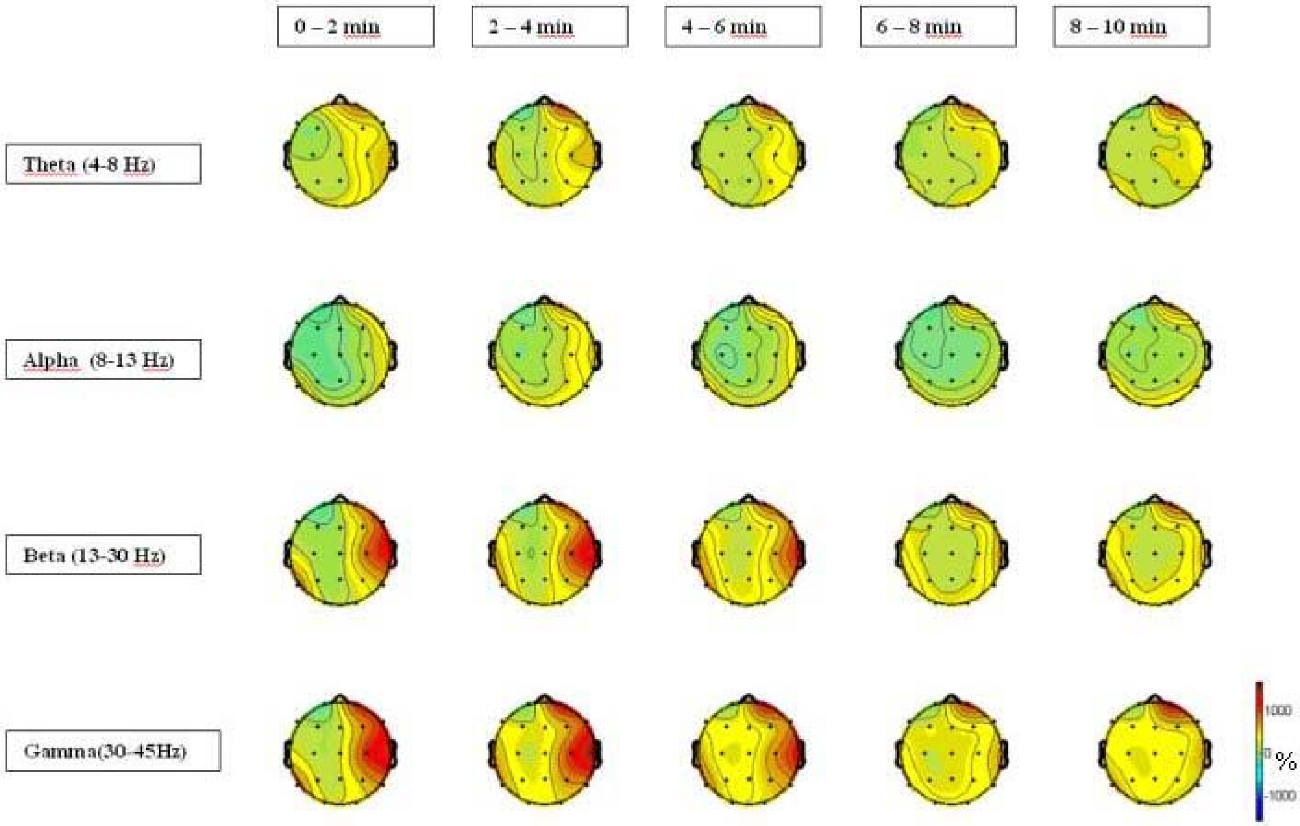

Fig. 3. Topographical maps of cerebral synchronization and desynchronization (mean values, calculated over the entire population). Each row represents an EEG rhythm and each column represents one of the five temporal periods in which the test was divided. Maps show rhythms lateralization, and powerful activities in beta and gamma bands, fading during the last temporal periods of the CPT test.

and desynchronization were evaluated, according to the following expression:

$$\Delta P_j(i) = \frac{P_j(i) - P_{Rj}}{P_{Rj}} \times 100 \qquad (1)$$

where $P_j(i)$ is the current power value in the j band, and P_{Rj} is the average power in the same band, calculated during the rest condition [9]. The $\Delta P_j(i)$ were averaged on time windows of 2 min for map representation and for comparison with behavioural results. Finally, for each of the five periods of the CPT test, four topographical maps were drawn, corresponding to the four EEG rhythms.

III. RESULTS AND DISCUSSION

1) Behavioral results and discussion

Overall mean reaction times during CPT test were 197.15 ± 21.73 ms for correct answers and 167.14 ± 11.28 ms for wrong answers. Mean omission errors number was 2.0 ± 2.35, and mean commission errors number was 7.56 ± 3.09.

The largest number of omission as well as commission errors was committed in the third period of the test (4-6 min), in accordance with previous clinical literature [10] and with Conners' CCPT-II standard [11], that reported a fall in subjects' attentional performance right in the middle of CPT test. The errors rate analysis showed that the subjects performances widely fell within the normality range as reported in Conners' CCPT-II standard [11].

2) EEG results and discussion

Fig. 3. shows the time courses of the % power variation of the considered frequency bands. Theta activity was always present, even if less powerful than beta and gamma activities. Theta rhythm took the shape of an extremely steady, poorly focused EEG activity, centered upon the fronto-central area, and spread over frontal and parietal regions, quite symmetrically over both the hemispheres. Weak signal power and strongly widespread appearance supported the assumption that theta activity generates in hippocampus [3], or at least in deep structures of the brain, in line with those works which interpreted theta as an index of subject's mental *arousal*. Alpha activity revealed to be mainly located on parieto-occipital region; and a powerful, roaming and lateralized beta rhythm was found.

Low gamma band showed powerful activity for each subject, with a focus located in the right temporal area. In five subjects, this peak slowly slid to the posterior area; in four of them it turned to the fronto-central region. In all cases it tended to rearrange its localization and compensate lower rhythms' shifts, interposing its focus between alpha and beta localizations.

These findings match with the assumption of Fitzgibbon [3] and others [12] who asserted that gamma activity could have a "binding" role, joining information coming from neuronal sub-structures located all over the brain. In our work, gamma activity appeared as a linking rhythm, mediating frontal (attentive) activation, occipital activity caused by neural networks involved in visual processing, and occipital alpha contribution related to *habituation.*

Synchronization during CPT test showed higher values in the right hemisphere, in each considered frequency band, in eight out of nine subjects (Fig. 3). Moreover, we found a right frontopolar ΔP_+, generalized at each frequency. This result was in agreement with previous literature [13], that ascribed sustained attention mainly to 9 and 11 Broadman's areas and to right fronto-parietal thalamic networks. Both theta and alpha ΔP_+ exhibited lower values compared to beta and gamma ΔP_+. Moreover, they shared a non-symmetrical distribution, with a faint ΔP_- all over the left side. Beta and gamma ranges showed a strong power increase, with respect to the rest condition, since the very beginning of CPT test administration. The right fronto-temporal area was involved in a deep synchronization, which faded during the test ongoing.

Statistical analysis demonstrated that power trends in high EEG frequencies strongly correlated with errors committed in answering the CPT test. Lower EEG bands showed weaker correlation (Tab. 1.).

Influence of finger movements in the beta range was investigated too. Two additional right-handed subjects underwent the CPT test and were asked to press the right mouse button every time they saw a letter, with no distinction between target and non target. EEG signals were recorded and processed. No beta activity was found over the contralateral central area (lead C3), corresponding to the motor and sensory cortex.

IV. CONCLUSION

This study tried to investigate surface EEG activity during a Conners' CPT test administration in a healthy population, and to correlate CPT's behavioural indexes with EEG data.

Evidence was presented here which supports previously documented EEG activity reflecting phasic attention during sustained attention tasks. Moreover, statistical analysis demonstrated that power trends in high EEG frequencies strongly correlated with errors committed in answering the CPT test. For this reason, we encourage the introduction of EEG investigation during the clinical assessment of sustained attention performance.

The present study could also be seen as the step of settlement of a normality range, to which eventually relate results obtained from a post-injured population, whose data will be processed in the very near future. We believe that a better knowledge of cerebral rearranging mechanisms (brain plasticity) which take place in patients who, after a brain injury, recover good skill in sustained attention could have interesting and useful implications in clinic and in rehabilitation.

TABLE I
CORRELATIONS BETWEEN ΔP VALUES AND TOTAL ERRORS (SIGNIFICANT VALUES INDICATED WITH *).

Electrodes	Corr. Alpha/ Total errors	Corr. Beta/ Total errors	CorrGamma/ Total errors
F7	0,3327*	0,4026*	0,3993*
F3	0,2637	0,3555*	0,3374*
Fp1	0,3030*	0,2529	0,2221
Fz	0,2730	0,3214*	0,3218*
Fp2	0,1327	0,2013	0,1684
F4	0,1566	0,1244	0,1223
F8	0,2009	0,1909	0,1653
T3	0,2895*	0,3060*	0,2719
C3	0,2422	0,3523*	0,3052*
Cz	0,2143	0,3263*	0,3210*
C4	0,0508	0,0011	0,0301
T4	0,1675	0,1893	0,1418
P3	0,2694	0,3126*	0,3144*
Pz	0,1681	0,2699	0,2872
P4	0,1529	0,1460	0,1862
T5	0,2994*	0,3477*	0,3407*
O1	0,1841	0,2411	0,2267
O2	0,1156	0,2310	0,2410
T6	0,3108*	0,3117*	0,3540*

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