6th Annual International IEEE EMBS Conference on Neural Engineering
San Diego, California, 6 - 8 November, 2013

Effects of Age-Related Cognitive Deficits on EEG Phase Coherence*

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Abstract— **Body and brain undergo several changes with aging. One of these changes is the loss of neuroplasticity, which leads to the decrease of cognitive abilities. Hence the necessity of stopping or reversing these changes is of utmost importance to contemporary society. In the present work, electroencephalogram (EEG) markers of cognitive decline are sought whilst the subjects perform the Wisconsin Card Sorting Test (WCST). Considering the expected age-related cognitive deficits, WCST was applied to young and elder participants. The results suggest that coherence on theta and alpha EEG rhythms decrease with aging and increase with performance. Additionally, theta phase coherence seems more sensitive to performance, while alpha synchronization appears as a potential ageing marker.**

I. INTRODUCTION

The process of healthy aging often involves loss of synaptic contacts and neuronal apoptosis, which can lead to declines in the episodic and working memory functions. Neural redundancy and plasticity, alongside with mental and physical training, promotes maintenance of brain activity avoiding the appearance of neuronal impairments, such as Alzheimer's disease and mild cognitive impairment [1-2]. In several studies, the electroencephalogram (EEG) has been used to determine which neuronal areas, their cognitive function and rhythms, are altered with aging [1]. Working and episodic memory studies have been reporting an increase of theta activity during the encoding phase [3]. Alpha activity has been associated to attention and binding processes [3-4]. Among other measures, these studies often apply coherence analysis to detect inter-regional EEG activation changes, both for stimulus-locked and background activations [5].

The Wisconsin Card Sorting Test (WCST) is a common neurophysiologic task used to evaluate complex cognitive functions such as working memory and rule shifting. Although WCST has been used to detect frontal dysfunction, recent studies show that the WCST is sensitive but not specific of the frontal regions malfunctioning [6]. A good performance in the WCST involves other brain regions besides the frontal areas, such as parietal and temporal locations [6].

In this study we analyzed the effects of age-related cognitive deficits on EEG phase coherence among frontal and parietal locations. The region pairs with EEG coherence consistently affected by cognitive deficits may be regarded as neuronal markers of good/bad performance in the WCST, with potential application on neurofeedback protocols. Considering the expected decline of cognitive performance with increasing age, young and elder subjects performed the WCST while the EEG signal was acquired. The correlation between EEG phase coherence and performance measure and age allowed us to identify potential neuronal markers for good/bad performance.

II. METHODOLOGY

A. *Subjects*

The EEG signals were acquired from 62 subjects: 19 subjects aging between 20 and 35 years old (10 females and 9 males) and 43 subjects aging more than 55 years old (17 females and 26 males). In both groups all subjects were right-handed and had normal or corrected vision. All subjects answered a questionnaire about their qualifications, personal and family medical records. All subjects participated voluntarily and signed an informed consent about the usage of data collected during experiments. The elderly subjects, unlike the young ones, were recruited from a larger cohort of an aging study and thus, were previously submitted to a battery of neuropsychological tests (memory, executive function and cognitive function tests). From the performance measures of the neuropsychological tests, the elderly subjects below the 25 percentile and above 75 percentile were selected to be included in the current study [7]. These persons, in general, had a low academic degree, were mostly retired, and did not have any neurological pathology diagnosed. The young subjects had a high academic degree, were actively workers and also did not have any neurological pathology diagnosed.

B. *Electroencephalogram acquisition*

The system used for the EEG recording was the 10-20 system, as represented in Figure 1a, from the Quickamp®, Brain Products, GmbH. The OpenVibe® software was used to acquire the EEG signals, to implement the synchronization between data acquisition and graphical user interface, and to save data for offline analysis.

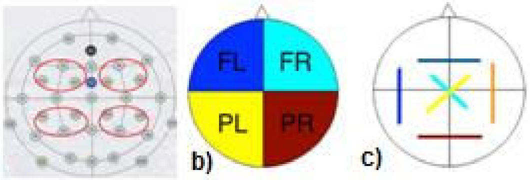

Figure 1: a) Electrodes arrangement used in EEG recording and the selected electrodes to the analysis. Colour scheme for b) the channel pooling and c) coherence analysis: FL-frontal left; FR-frontal right; PL-parietal left; PR-parietal right.

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*Research co-sponsored by the Portuguese Foundation for Science and Technology and COMPETE program.

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The subjects were sited, in an illuminated and acclimatized room, distancing 50-70 cm from the computer screen with touch technology. We asked all subjects to answer as correct and as quickly as possible, to answer always with the same hand, and not make any movements beyond the required ones. Each subject performed 3 sessions of the WCST, while the EEG signals were recorded with a sampling frequency of 1024 Hz. Before each WCST session, a 30s baseline was recorded, during which the subjects were instructed to look at the computer's monitor in black and to be as relaxed as possible.

C. *Wisconsin Card Sorting Test*

The Wisconsin Card Sorting Test is constituted by 4 decks of cards that differ according to 3 categories: colours (red, green yellow and blue), shapes (triangle, star, cross and circle) and number of symbols (from 1 to 4), as shown in Figure 2. When a card appears at the bottom of the screen, the subject has to match it to one of the 4 decks on the top of the screen, following one of the 3 categories mentioned. The subject has to touch in the deck that matches the card according to the category in use. The feedback (right or wrong) is given to the subject as soon as he chooses one of the 4 decks. Once the subject discovers the category in use, he should answer accordingly until it is changed (after 10 correct card matches). When the category in use is changed, the subject has to discover the new category to be applied, which is always different from the previous one. The test ends after 9 completed categories or when the subject completes 128 cards [6].

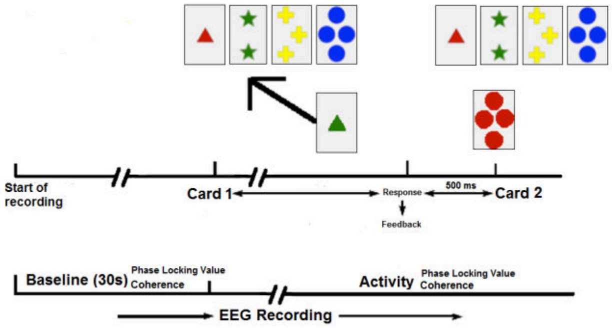

Figure 2: Schematic representative of the Wisconsin card sorting test and the segments used for the spectral coherence and the phase coherence analysis, adapted from [5]**.**

The performance measures considered from the WCST are: completed categories, perseverative errors and non-perseverative errors.

D. *Signal Pre-Processing*

The software selected to analyse the EEG signals was the Analyzer 2®, Brain Products, GmbH. After filtering the signals (band pass: 0.3-100 Hz and Notch filter in 50Hz) and correcting the ocular artefacts with an algorithm based on independent component analysis [8-9], the EEG signals were segmented. The signal was divided in segments of 5s between the appearance of the first card and the last feedback and for the 30s baseline period (Fig. 2). The motor artefacts were removed by rejecting the segments with amplitude signals higher than 500 μv and also with the difference between the maximum and minimum values higher than 1000 μV. In order to increase the independence of the signals between neighbouring electrode locations, the current source density method was previously applied on filtered data.

Only 12 electrodes (Figure 1a) were used to calculate coherence for theta (4-8 Hz) and alpha (8-13 Hz) frequency bands. The frequency limits were adjusted on each frequency band according to each subject's alpha peak. Four neuronal regions were selected for analysis according to Figure 1b: (FL) frontal left, (FR) frontal right, (PL) parietal left and (PR) parietal right. As a result of channel pooling, the averages of three channels per area were considered (Figures 1b and 1c): (1) frontal left: FC5, F3 and FC1; (2) frontal right: FC6, F4 and FC2; (3) parietal left: CP5, P3 and CP1; (4) parietal right: CP6, P4 and CP2.

E. *Spectral coherence analysis*

Spectral coherence analysis was performed as a preliminary measure of inter-region EEG synchrony. The coherence of the EEG signals from two electrodes is a measure of the degree of association between the spectra of the two channels, providing information about the functional coupling between two neuronal areas [10]. The coherence was calculated using (1):

$$\mathrm{Coh}_{ij}^{2}(\omega)=\frac{E\left[(C_{ij}(\omega))^{2}\right]}{E[C_{ii}(\omega)]E\left[C_{jj}(\omega)\right]}, \qquad (1)$$

where $C_{ij}(\omega)=X_i(\omega)X_j^*(\omega)$ is the cross-correlation coefficient between the Fourier transform of the EEG signals of channel i and channel j [10]. The coherence was analysed during the baseline period as well as during the WCST performance (Figure 2). Figure 1c presents the colour scheme for the coherence between the 4 channel pools.

F. *Phase coherence analysis*

In order to assess accurately how the phase coherence among different EEG locations is affected by age and WCST performance, the phase locking value (PLV) was calculated. The signal of each electrode was initially filtered in the theta and alpha bands with a zero-phase FIR filter. The instantaneous phase and instantaneous amplitude for each signal were then obtained from the Hilbert transform of the filtered signals. The resultant phase vectors for each channel were segmented in windows of 5s for all the timeframe of the WCST (between the appearance of the first card and the last feedback) and for the 30s baseline period. Phase coherence was calculated with an adapted implementation of the PLV measure [11]. The PLV measures the consistency of phase difference at each time-point across trials as:

$$PLV_t=\frac{1}{N}\left|\sum_{n=1}^{N} exp\left(j\theta(t,n)\right)\right| \qquad (2)$$

Where θ(t,n) is the phase difference between the instantaneous phase of each signal (ie. $\theta_1(t,n) - \theta_2(t,n)$) for each time-point (t) at each trial (n).

Since our analysis focused on continuous data and not on stimulus locked data, the PLV measure was adapted to measure the consistency of phase difference within each time window. This means that, unlike the original implementation of PLV, the phase differences were averaged for all time points within each time window and not for each time-point across trials. An average PLV was calculated for each pair of electrodes in each session of each participant by averaging all PLV values calculated for each window of that session for that pair of electrodes. The phase locking statistic (PLS) was calculated to assess the significance of the calculated PLVs. One hundred surrogate datasets were constructed by shuffling the position of the windows in one of the electrodes for each electrode pair. The PLV of each surrogate pair was calculated and the original PLV was considered significant if less than 5% of the surrogate datasets produced a higher PLV than the original PLV (PLS <5). Only significant PLVs for each electrode pair were averaged across sessions for each subject. The mean PLV for each group was given by averaging the mean PLV of each subject within each group.

G. *Statistical Analysis*

All subjects were ranked according to the Z-score (combined measure of the individual performance measures: completed categories, perseverative errors and non-perseverative errors) and age. Using a K-means cluster analysis, three groups were defined according to age and performance on WCST: elders with bad performance (E-BP), elders with good performance (E-GP), and young with good performance (Y-GP). Then all values from each EEG feature were organized according to the experimental groups. The one-way ANOVA was calculated for EEG coherence, for the 4 channel pools (baseline and during the WCST), in order to access if there were any significant differences (p-value < 0.05) between the three groups. The PLV measure was correlated (Pearson correlation) with the Z-score and age. The statistical analysis was performed using Matlab® and OriginLab®.

III. RESULTS

Figure 3 shows subject scatter according to performance in WCST (z-score) and age. According to this distribution, 3 groups were defined: Y-GP, E-GP and E-BP. Although cognitive performance decreases with age (Fig. 3), some elder subjects performed as good as the young subjects. With this group distribution, age and cognitive performance effects on EEG phase coherence were investigated.

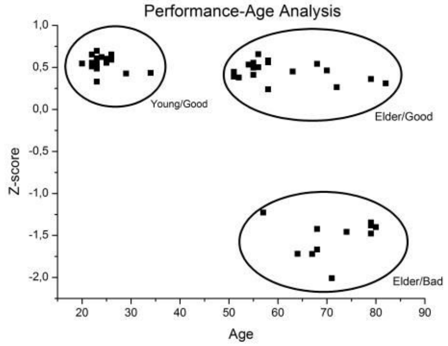

Figure 3: Distribution of the subjects according to the performance measure (Z-score) and age.

Figure 4A show the results of the average and standard-deviation of coherence on theta and alpha rhythms, for the 3 WCST sessions, for each region pairs: frontal left-frontal right (FL-FR), frontal left-parietal left (FL-PL), frontal left-parietal right (FL-PR), frontal right-parietal left (FR-PL), frontal right-parietal right (FR-PR) and parietal left-parietal right (PL-PR). All region pairs, except for frontal left-parietal left, distinguish significantly between the Y-GP and the E-BP group. The frontal left-parietal right and the frontal right-parietal left pairs also showed significant differences between the E-GP and E-BP group, and the Y-GP and E-GP, respectively. The group differences showed to be more significant for WCST data than baseline data. Figure 4B shows a schematic representation of the PLV significant differences for all 3 group comparisons, on theta and alpha rhythms. In Figure 4C, the group average and standard-deviation of the theta and alpha PLV values, for each neuronal connection are represented. Figures 4B and 4C show that coherence on theta rhythm on frontal areas (left-right hemispheres) and fronto-parietal areas significantly distinguish between Y-GP and E-BP groups, and also between E-GP and E-BP groups. As for the alpha rhythm, (Figures 4B and 4C) the same areas (frontal and fronto-parietal) significantly distinguish between Y-GP and E-BP groups, and also between Y-GP and E-GP groups. The correlations theta PLV vs. Z-score and alpha PLV vs. Age passed the significance test and are represented in Figure 4D. Unlikely, the correlations theta PLV vs. Age and alpha PLV vs. Z-score didn't prove to be significant.

IV. DISCUSSION

The present work intends to study the effect of age-related cognitive deficits on EEG phase coherence. As presented on Figure 4A, coherence on theta and alpha rhythms, for all the neuronal areas, decrease with performance decline and age, respectively. Although the results for the phase coherence analysis support this finding (Figures 4B and 4C), the decline of phase coherence in theta rhythm is more evident between the good and bad performance, since the Y-GP and the E-GP present very similar values of PLV. Concerning the alpha rhythm, E-GP and E-BP groups have similar PLVs and statistic separates better between groups with different age rather than distinct performance. The correlation between theta or alpha PLVs and age or performance suggests the same trend: theta phase coherence could be regarded as a performance marker and alpha phase coherence as an age marker (Figure 4D). Our findings may indicate that, to achieve a good performance in the WCST a high coherence on theta and alpha rhythms are necessary, especially between the frontal and fronto-parietal areas, which are associated to working memory, executive functions and attention [6].

High coherence is related to augmented linear functional connections and information transfer, which is crucial to a correct use of working memory, binding and attention processes and also executive functions [1, 5]. These results are in agreement with other studies that have shown a decline of coherence with age and associated deficits in cognitive function [5, 12]. Coherence on theta rhythm significantly distinguishes performances on WCST, as it seems to be associated to the encoding and retrieval of working memory, which is of utmost importance to achieve a successful performance in the WCST [3, 6].

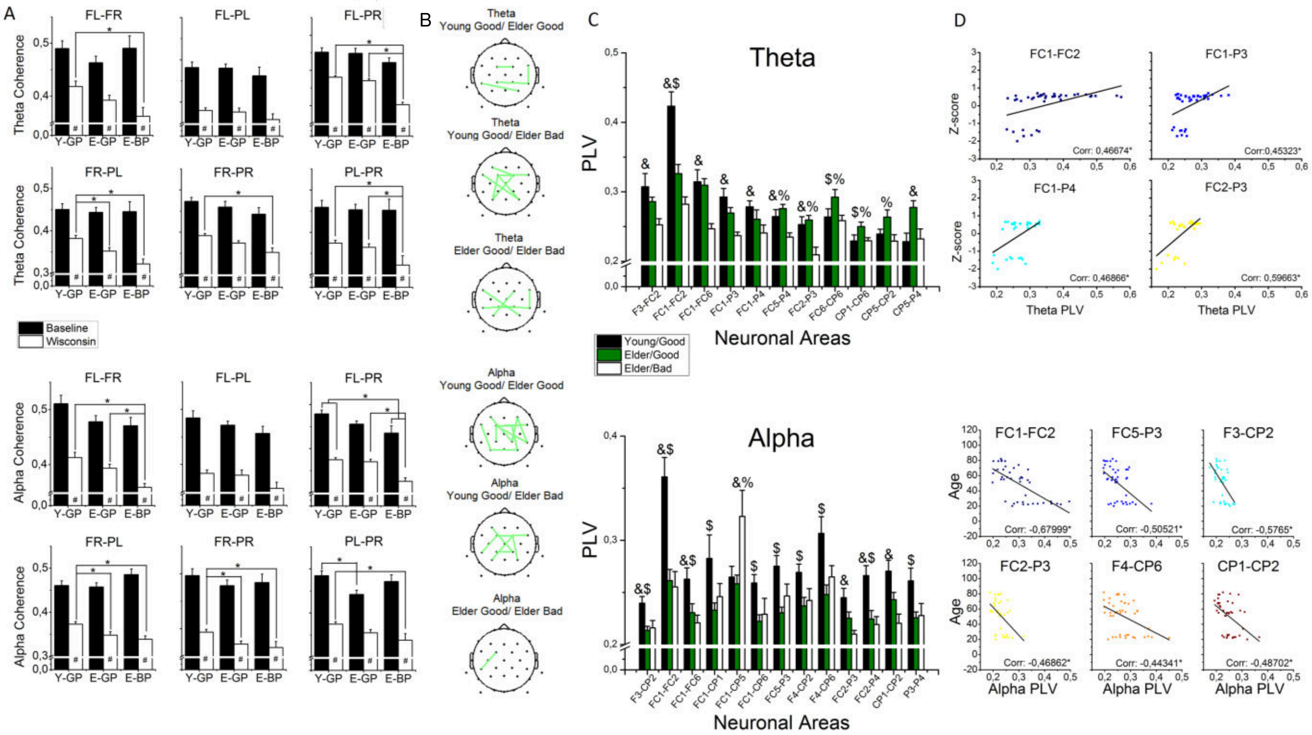

Figure 4: A) Average and standard-deviation of coherence on theta and alpha rhythms for each performance-age groups. The * represents the significant differences between the groups (p-value<0.05) and the # represents the significant difference between the baseline and the WCST (FL-Frontal Left, FR- Frontal Right, PL-Parietal Left, PR-Parietal Right; B) Schematic representation of the PLV significant differences between performance-age groups, for theta and alpha; C) Average and standard-deviation of theta and alpha PLV for each performance-age group. The & represents the significant difference between the Y-GP and E-BP group; the $ represents the significant difference between the Y-GP and E-GP group; and the % represents the significant difference between the E-GP and E-BP group. D) Pearson correlation between theta and alpha PLV and the performance measure (Z-score) and age, respectively. The value of the correlation and the best-fitting linear function is also represented.

In our study, alpha coherence distinguishes significantly the age groups (but not performance groups), which is in line with the fact that aging leads to decrements in control processes of working memory, such as the inhibition of irrelevant information and binding process [13]. As so, we hypothesize that although E-GP group presents an aging phenotype it still performs successfully in the WCST probably because they managed to keep a high coherence between theta rhythms of frontal and fronto-parietal locations, which is very important to the correct use of working memory.

ACKNOWLEDGMENT

This work was co-sponsored by FCT – Foundation for Science and Technology and Compete Program with the project reference FCOMP-01-0124-FEDER-021145 (PTDC/SAU-ENB/118383/2010).

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