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Frontal EEG theta changes assess the training improvements of novices in flight simulation tasks

G. Borghini, P. Aricò, L. Astolfi, J. Toppi, F. Cincotti, D. Mattia, P. Cherubino, G. Vecchiato, A. G. Maglione, I. Graziani and F. Babiloni

Abstract— **The aim of the study is to analyze the variation of the EEG power spectra in theta band when a novice starts to learn a new task. In particular, the goal is to find out the differences from the beginning of the training to the session in which the performance level is good enough for considering him/her able to complete the task without any problems. While the novices were engaged in the flight simulation tasks we recorded the brain activity by using high resolution EEG techniques as well as neurophysiologic variables such as heart rate (HR) and eye blinks rate (EBR). Results show clear changes in the EEG power spectra in theta band over the frontal brain areas, either over the left, the midline and the right side, during the learning process of the task. These results are also supported by the autonomic signals of HR and EBR, by the performances' trends and by the questionnaires for the evaluation of the perceived workload level.**

I. Introduction

It is well know that a main difference between experts and novices is that when doing the same activities, the second ones need more cognitive resources and engagement than the first ones [1]. The novices can reach good level of performances and then become fully confident with the activity by training and experiencing different difficulty levels of the task. For example, when we drive for the first time, we pay high attention to a lot of details. After a while we are able to drive, probably better than the first time, and to do other things at the same time (legitimately). A reasonable assumption is that the amount of cognitive resources employed, from the first time they approached the new task, has changed. These changes in cognitive processing are then probably reflected in a variation of the activity of several cortical areas. The alteration of the cortical activity during the execution of particular tasks has been investigated by using different neuroimaging methods (reviewed in [1]). Neuroelectrical imaging by using electroencephalography (EEG) is one of the most interesting tools, since it provides the required time resolution needed to follow the brain activity along the execution of the tasks. It has been often reported in literature that one of the most prominent event linked to the increase of the cognitive effort during a task is the increase of the EEG power spectrum in the theta frequency band [2][3]. Such increase occurs typically over the prefrontal and frontal areas, often located in the midline scalp position Fz. In this paper we attempted to reverse such robust finding by hypothesizing that a decrease of the frontal theta during the training of a particular task could be taken as an index of the correct acquisition of the task and experience by the novice. In fact, it is important to note that the overt behavior of the pilot during a task is not a good sign of the perceived difficulty of the task itself. Two pilots (say A and B) could perform the same task with very different levels of the perceived difficulty. In particular pilot A could perform the task without any cognitive effort while pilot B could perform the task by using "all" his/her cognitive resources. The idea proposed here is that it is possible to use the variation of the EEG power spectra in frontal areas in theta band as a sign of the novices' learning process. Such hypothesis was tested in 2 groups of normal subjects while they were learning to complete two types of flight simulation tasks. The brain activity was recorded during certain training sessions of the subjects along the week, together with the collection of other physiologic signs of mental and engagement states, such as the measurement of the heart rate (HR) and the eyeblinks rate (EBR). In fact, all these variables have been demonstrated to be correlated with the level of mental engagment during the execution of a task. In particular, it has been suggested that increased HR could be related with an increased mental workload while eye blinks (namely duration and frequency) are inversely correlated with the increase of the mental workload [4].

G. Borghini, P. Aricò and D. Mattia are with IRCCS Fondazione Santa Lucia, Rome, Italy.

A.G. Maglione is with Department of Anatomy, Histology, Forensic Medicine and Orthopedics, University of Rome "Sapienza", Italy.

L. Astolfi, J. Toppi and F. Cincotti are with the Department of Computer, control, and management engineering, Univ. of Rome "Sapienza" and with the Fondazione Santa Lucia Hospital, Rome, Italy.

F. Babiloni, G. Vecchiato, P. Cherubino and I. Graziani are with the Dept. Physiology and Pharmacology, Univeristy of Rome Sapienza, P. le A. Moro 5, 00185, Rome, Italy. (corresponding author phone: +39-3287697914; fax: +39-06-23326835; e-mail: Fabio.babiloni@uniroma1.it)

II. Material and methods

A. The proposed tasks

Flight Simulator X. The flight simulation software is the game Microsoft Flight Simulator X (FSX) and the task is one of the first missions for learning to control an airplane. The aim of the mission is passing through a specific sequence of 5 target gates by a delta plane. In particular, at the beginning of the task the pilot will be already flying with the delta plane (no take-off procedure requested) in front of the first target gate. Generally, when a gate is green it means that it is the active one, otherwise when it is red, it means "not active". All the gates are numbered and the right path is from the number 1 to the number 5. If the pilot skips one gate, that is, it does not pass through it, he will not be able to finish the mission until he does not pass through active one. The performance of the flight simulation is calculated as the number of completed missions in 30 minutes. The statistical significance of the results has been evaluated by the repeated measures ANOVA and then by the multiple Duncan's pairwise comparison ($p<0.05$).

Multi Attribute Task Battery (MATB). The MATB [5] is a computer-based task designed to evaluate operator performance and workload. The experimental platform requires the simultaneous performance of tasks that are generalizations of piloting tasks: tracking (TRCK), auditory monitoring (COMM), resource management (RMAN), and response to event onsets (SYSM). The demand of the system monitoring task is monitoring the gauges and the warning lights by responding to the absence of the Green light, the presence of the Red light, and monitors the four moving pointer dials for deviation from midpoint. The demands of manual control are simulated by the tracking task. The subject keeps the target at the center of the window by moving the joystick. This task can be automated to simulate the reduced manual demands of autopilot. Subjects are also required to respond to a communication task. This task presents pre-recorded auditory messages to the operator at selected intervals during the simulation. However, not all of the messages are relevant to the operator. The subject's task is to determine which messages are relevant and to respond by selecting the appropriate radio and frequency on the communications task window. The demands of fuel management are simulated by the resource management task. The goal is to maintain the main tanks at 2500 units each. This is done by turning On or Off any of the eight pumps. Pump failures can occur and are shown by a red area on the failed pump.

B. EEG and physiological recording

Electroencephalogram (EEG) and physiological signals, eye blinks (EB) and electrocardiogram (EKG), were recorded by a digital ambulatory monitoring system (Brain Products GmbH, Germany). Sixty-one EEG channels and one EKG channel were collected simultaneously during the experiment with a sampling frequency of 200 (Hz). All the electrodes were referenced to both the earlobes and the impedances were maintained around 10 (kΩ). Electrode for the heart activity was positioned on the Erb's point. A 50-Hz notch filter was applied to all measurements for removing power interference. The EEG recordings was also band-pass filtered (low-pass filter cut-off frequency: 40 (Hz), high-pass filter cut-off frequency: 1 (Hz)) and then the Independent Component Analysis (ICA) was used in order to remove the artifacts from the data. By the separation of the independent sources, the EB component was analyzed for the estimation of the EBR, while the EKG raw signal was used for estimate the HR. The EEG data have been analyzed by the Fourier analysis in the frequency domain and the Fast Fourier Transform (FFT) has been used for the Power Spectral Density estimation (PSD) in the frequency bands, theta and alpha. The considered bands have been defined by the Individual Alpha Frequency (IAF) value [6]. All the indexes have been normalized by the z-score transformation, for direct inter and intra – subjects comparisons across the different training sessions, respect to the reference condition, in which the subjects watch the stimuli's tasks but without answering to them.

C. High resolution EEG cortical estimation

Cortical activity from EEG scalp recordings was estimated by employing the high-resolution EEG technologies, including the use of quasi-realistic head model, estimation of cortical sources by solving the EEG linear inverse problem with distributed sources, and statistical parametric mapping of significant increase or decrease of EEG spectral activity over the cortex [7][8].

D. Experimental groups and protocols

The subjects were selected by their ages (26.7±1.8) and computer game skills, in terms of resources allocation, focusing on goals and motor coordination. They were volunteers and experimental instructions were provided at the beginning of the experiments. They were also said to not worry in case of crash or difficulty in controlling the delta plane or facing the MATB subtasks during the first sessions, in which the familiarization with the mission and task were the goals. The experimental protocols consist in 5 days, from Monday to Friday, with a training session of 30 minutes every day at the same time. On the first, the third and the fifth day the brain activity of the subjects have been recorded. At the end of the week 3 EEG recordings, 5 performance datasets and the total scores of the NASA – TLX questionnaire have been collected for each subject. Two groups of 5 subjects have been evaluated for each type of the experimental protocols.

III. Results

A. Tasks performances

As expected, throughout the training sessions the performance of both tasks increased. Figure 1 shows the performance's indexes of the FSX (on the top) and of the MATB task (on the bottom).

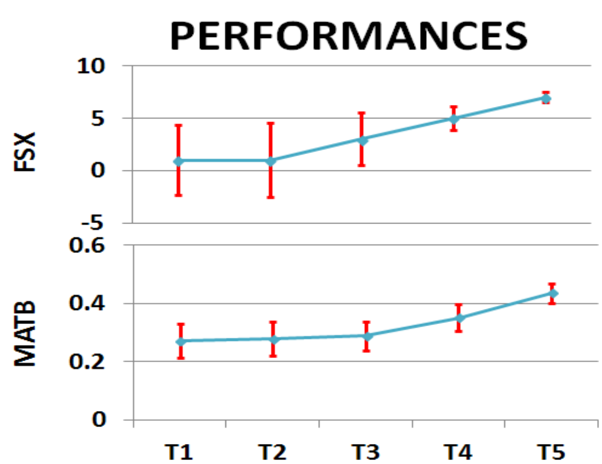

Figure 1. Performances of the FSX (on the top) and of the MATB (on the bottom) task. In blue color the mean performances have been reported with the mean standard deviations of the performance's indexes.

The estimation of the FSX performance was done by counting the number of completed missions within 30 minutes respect to the crashes and considering that the fastest mission lasted 4 minutes. For the MATB there have been defined 4 different indexes, one for any sub-task, and then a global index has been calculated as mean value of the others. It is important to note the simultaneous increasing of both the performances level and the decreasing of both the standard deviations. They represent how the subjects improved their skills and results with more accuracy than in the previous sessions. For example, in the FSX task the first performance of a subject was 4 crashes and 1 completed mission, while at the end he did 7 completed missions without any crashes. Obviously, the total time was always of 30 minutes and by the results it is easy to understand how this subject improved his skills about the control of the delta plane and his ability in passing through the target gates.

B. Perceived workload

At the end of each training session, the subjects filled the questionnaire NASA - TLX for the evaluation of the perceived workload. The increasing of the abilities for completing the tasks is still well showed by the trends of the NASA – TLX total scores shown in Figure 2. After the T3 session, especially for the FSX, the subjects started to understand well how to do the tasks and they gained more confidence by feeling less workload level than the previous sessions. Comparing the NASA – TLX results with the performances' trends (Figure 1), it becomes obvious how after the third session the subjects started to improve their performances and to feel more familiar with the tasks. In fact, from T3 onward, the performance levels increases and the NASA-TLX decreases appreciably.

B. Frontal theta power spectral density

The analysis of the EEG signals brought important results confirming those previously discussed. In Figure 3 the mean z-scores of the frontal theta PSD are reported. In particular , the PSD calculated in the theta band in the 3 different training sessions over the frontal midline channel Fz is shown. However, the discussion is valid for the left and right frontal sides as well, over the channels F3 and F4, respectively.

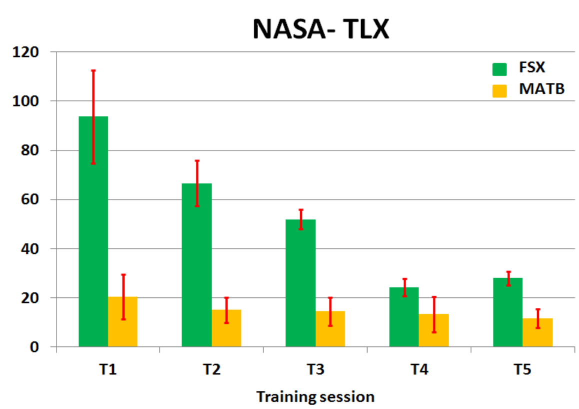

Figure 2. Mean NASA – TLX total scores filled at the end of each training session. Both the trends of the FSX task (green) and of the MATB task (orange) are decreasing, indicating that the subjects are getting familiar with the task and feeling more relaxed during the execution of them.

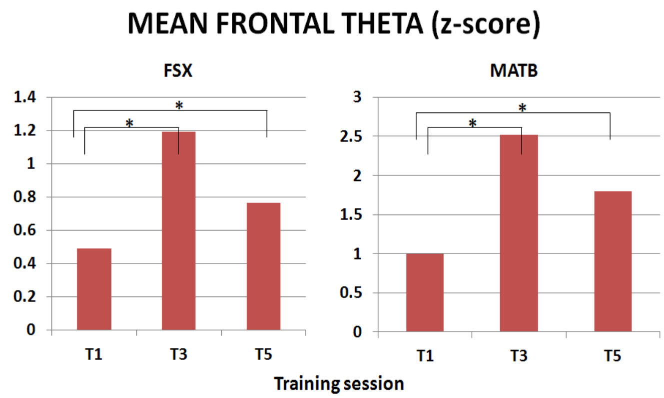

Figure 3. Mean frontal theta PSD during the FSX (left side) and of the MATB (right side) EEG recording sessions estimated for the Fz channel. In general, the PSDs of the third (T3) and of the last session (T5) were statistically different (*) from the PSD of the first one (T1). Statistical analysis: repeated measures ANOVA ($F=20.78$, $p<0.05$) and multiple Duncan's pairwise comparison ($p<0.05$).

Before the first session (T1) the subjects received the instructions for executing the mission and then they tried to do it as well as possible. Obviously they did not know how to do it properly and they had to practice and to take confidence with the manual and cognitive processes involved in the tasks before being able to complete them without requiring lots of cognitive resources and time demand. The trends in the figure could represent well the learning process from the first time the subjects faced the tasks (T1) to the moment in which they learnt how to do it properly (T5). After the first times in which they learnt how performing the tasks, they used their own strategies for executing them and obtaining good performance, but requiring less mental engagement. In particular, the brain activity in the theta band over the left, central and right frontal areas decreased respect the session in which they got completely into the tasks (T3).

D. Cortical maps

By the cortical maps analysis is possible to note the trend of the supposed learning process mention earlier for both the tasks. Figure 4 reports the cortical maps of the 3 EEG recording sessions estimated in the theta band. The colored areas are the statistically significant differences between the reference condition and the considered task. A red color means that the PSD estimated during the task is statistically higher ($p<0,05$, Bonferroni corrected for multiple comparisons) than the PSD estimated during the reference condition; vice versa, when the difference is blue. The firsts on the left side are the cortical maps of the first training session and it is easy to note how only few brain areas are involved in the execution of the tasks. This happens because the subjects were trying and experimenting different strategies with a consequent poor behavioral outcome as represented in Fig.1 for T1 and T2. In fact, the topography of the involved brain areas could be randomly selected. For example, in the T1 – MATB session the active brain areas

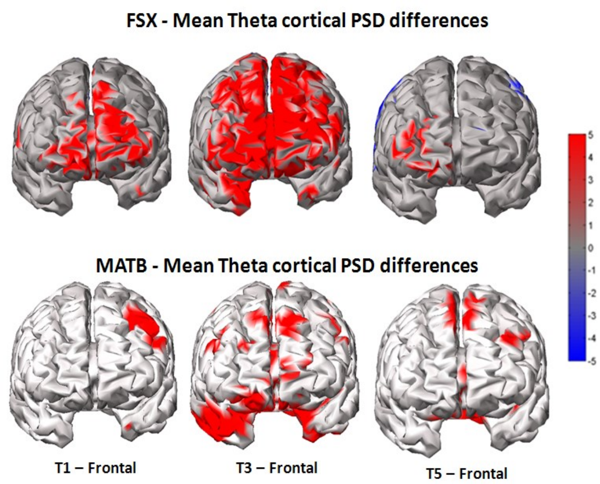

Figure 4. Mean cortical maps of the theta PSD differences between the considered task and the reference conditions. They represent the estimation and the evolution of the theta rhythm across the training sessions of the FSX and MATB tasks. Left side: cortical maps of the first session (T1), in the center of the third session (T3). Right side of the last one (T5).

are not the expected ones, that is the frontal areas, but the central – left area, over the sensory – motor cortex. After a couple of training sessions the subjects got higher confidence with the tasks and they started to understand how to face them and how to improve their performances. In fact, in the third EEG recording (T3) they started to pay more attention to the tasks, the EBR were lower than the first session ($p<0.05$), and to involve more brain resources. This means a vast amount of involved brain areas, especially in the frontal parts of the brain and in the theta band. As shown in the central part of Figure 4, almost all the frontal lobes are involved in the third session of both the experimental tasks, the FSX (on the top) and the MATB (on the bottom). Once the subjects found their own strategy, they improved their skills and in the fifth training session (T5) they were able to complete the tasks requiring and involving less brain areas and cognitive resources. The cortical maps on the right side of Figure 4 show only few red brain areas, but the biggest differences respect to the others are the performances improvement.

E. Autonomic signals

The information represented by the brain signal analysis are also supported by the autonomic signals of HR and EBR. The mean values of these parameters showed decreasing trends from the first to the last training session. Lower HR ($F=148.79$, $p<0.05$) and EBR ($F=9.76$, $p<0.05$) values during T5 means that the subjects felt more confident, they paid more attention to the tasks and that they could complete them more easily and accurately than the first time, obtaining higher performances than at the beginning.

IV. Discussion

The results obtained in the analyzed population suggest that when the subjects increase their behavioral and task performances (sessions T3, T4 and T5) the corresponding PSD in theta band decreased significantly over the frontal areas. The perceived workload level and the autonomic parameters indicate lower levels of stress and pressure during T3, T4 and T5 than for the first session (T1). The occurrence of low values of PSD in theta band for T1 could be interpreted at the light of the poor outcome of the behavioral task. It seems from the debriefing that the subjects are not able to proper manage the tasks and then their level of mental engage were lower in T1 and T2 than in the T3, T4 and T5. In these last sessions the overt behavior increases while the PSD theta decreases as well. Such neuroelectrical parameters could then index the training level of the subject, other than his/her overt performances.

V. Conclusion

The results might be used as new criteria for evaluating the progress of novices, e. g. novice pilots, throughout their studies. The flight performance evaluation still depends on visual inspections, but different pilots can get the same flight accuracy involving different amount of cognitive resources. It could be interesting to create a database containing results averaged overall great numbers of expert pilots and obtaining standard results in certain flight situations or emergency conditions. Comparing these standards with the novices' cognitive results and flight performances, it should be possible to assess the progresses of the novice pilots at some point of their studies. It is obvious that by these criteria, the evaluation of the pilots could be more accurate. Also, it should be used as selection criteria for deciding which units the pilots are more prone to.

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