EEG monitoring during software development

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***Abstract*—This paper focuses on the analysis of experienced programmers' central nervous system response during a software development protocol. The main aim was to explore the neurological mechanisms (i.e., involved brain areas and rhythms) triggered by such a complex task. To do this, a 29-channel EEG signal was acquired on ten experienced programmers during a software development-like exercise. Then, the power spectral density at each EEG channel in standard Delta, Theta, Alpha and Beta bands has been computed and evaluated. The acquired subjects show on average a significant increase of Delta, Theta and Beta powers with respect to the baseline condition. Delta and Theta rhythms increase mostly in the frontal and parieto-occipital regions, while the Beta activity is more diffused. Furthermore, from the statistical analysis it emerged that the power increase in these three bands is significant in different time instants. Moreover, during the programming phase two subjects present a pronounced theta peak in the EEG power spectrum, while other two maintain an alpha peak, even if less pronounced with respect to the baseline condition. These results suggest the need for further investigations. This research is part of the Biofeedback Augmented Software Engineering (BASE) project, which aims at studying programmer's central and autonomic nervous systems response during the software development activity.**

Keywords—EEG bands, software bugs, attention, mental effort, workload

I. INTRODUCTION

Nowadays, the software development sector represents the biggest industry area worldwide. Software development is a human made very complex task, which asks programmers to elicit specific architectural and functional requirements by developing a huge amount of lines of code and testing them. This developing process involves very demanding mental tasks, such as mathematic calculation, symbols manipulation and recursive reasoning. For these reasons, even very expert developers, often generate software bugs. Indeed, different studies demonstrated that, even using sophisticated software generation techniques, the developed code may still contain a significant amount of errors [1, 2].

Generally, software bugs are difficult to find and the consequences of their presence in the code are unknown [3]. Moreover, the 5th edition of the Software Fail Watch from Tricentis (tricentis.com), estimated that the global cost in 2017 due to software failures was about $1.7 trillion. Therefore, a breakthrough in software reliability is of a great interest.

Some studies demonstrated a significative similarity among the different types of software bugs generally detected, despite of the methodologies and programming language used [4]. The tendency of programmers to generate the same kind of errors, suggests that a set of common mental patterns being related to bugs exists, making relevant the study of the physiological mechanisms at the basis of the generation of such software faults.

This is the main concept that stands under the BASE project: its central goal is to monitor programmers during the examination and generation of code by means of non-invasive sensors.

The few existing studies related to this topic mainly focused on the investigation of the brain mechanisms involved in software comprehension using brain signals and imaging techniques such as the Electroencephalography (EEG), functional magnetic resonance (fMRI) and functional near-infrared spectroscopy (fNIRS).

The fMRI study of Sigmund et. al showed that software comprehension involves brain areas related to working memory and language [5]. Furthermore, Nakagawa showed that it is possible to quantify programmers' mental workload basing on the cerebral blood flow measured with NIRS [6].

The fMRI study, reported in [7], analyzed the brain activation patterns related to the understanding of source code and the detection of functional bugs. A novel connectivity pattern related to the source code understanding, suspicion and consequent detection of bugs has been identified and a specific role of the insula in bug detection has been highlighted.

However, the BASE project proposes a very innovative approach, which aims at monitoring simultaneously the programmers' central nervous system (CNS) (e.g. electroencephalogram-EEG) and autonomic nervous system (ANS) (e.g. electrocardiogram-ECG) responses by means of non-invasive sensors.

By integrating different biological signals deriving from the ANS and CNS, it could be possible to relate in time the physiological state of the subject with the lines of code, introducing in this way a programmers' biofeedback. This kind of monitoring can allow to understand the brain

This work was supported by the BASE project, POCI - 01-0145 - FEDER- 031581

networks and mechanisms related to the loss of attention, the increase of mental effort and the generation/detection of bugs and to find the related autonomic responses. Moreover, introducing a time relationship between the generated lines of code and the physiological state of the programmer, it could be possible to identify more easily the portion of software that might contain errors due to a decrease of the subject's attention.

BASE has been organized in two main experimental studies. The first one has been held in Coimbra [2, 3], whereas the second study is still taking place at Politecnico di Milano.

Study [3] demonstrated that HRV signal can be used to evaluate the subject's mental effort during reading and interpretation of different code units. Furthermore, it has been also shown that pupillography is an effective method to measure programmers' mental effort and cognitive load [2]. This paper describes the preliminary results of the second study, which focus on the analysis of EEG activity of ten programmers during the generation of code. It has been noted a common enhancement of Delta (1-4 Hz) and Theta (4-8 Hz) rhythms both in the occipital and in the frontal areas with respect to a baseline condition. Moreover, a more spread Beta (13-22) power increase is observed. Additionally, during the programming phase, two subjects clearly show a theta peak in the power spectrum, while other two subjects present an alpha peak.

II. Materials and Methods

A. Subjects

A screening questionnaire was employed to select and estimate the subjects' level of proficiency in C programming. Specifically, the questionnaire proposes ten code snippets in C language and, for each of them, a multiple-choice question about its functioning. A volunteer is considered eligible for the test if he/she scores at least 4/10, i.e., four correct answers out of ten questions.

Ten volunteers (mean age 28, std 6.9), 6 males and 4 females, passed the screening procedure and were enrolled for acquisitions.

All participants signed an informed consent and their anonymity was guaranteed. The study was approved by the Ethics Committee of Politecnico di Milano.

B. Experimental setup

The experimental setup of the present study was designed in order to acquire in a synchronous way different programmer's biological signals. Specifically, it allowed to acquire EEG, fNIRS, ECG, EDA and respiratory signal. Moreover, the subject was also monitored by an eye tracker and a webcam installed on the PC screen that he/she used during the whole experiment. A second PC acquires EEG, ECG, EDA and respiratory signals, whereas the fNIRS is provided of a dedicated PC.

The synchronization trigger is sent from the fNIRS machine to all the other elements of the experimental setup.

EEG- the EEG signal is acquired from a 64-channel EEG cap by Micromed (micromed.eu). The raw data is sampled at 256 Hz and notch filtered at 50 Hz. For this study 29 channels are acquired (Fp1, Fpz, Fp2, AF7, AF3, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, Oz, O2).

C. Protocol

The experiment starts with the acquisition of a 2 minutes baseline condition, during which the subject is asked to type randomly on the keyboard with eyes closed. In such a way it is possible to 'clean' future results from any physiological response related to the typing task.

After the baseline acquisition, the volunteer has to perform three different tasks: i) neutral text reading (60 s), ii) C code snippet reading (300 s), and iii) programming exercise in C language (20 min maximum). For each task, two possible alternatives were selected, i.e., two different neutral texts, 2 different code snippets and two different programming exercises. Specifically, two levels of difficulty were selected for the programming exercises.

A neutral text, a code snippet and a programming exercise are randomly selected from the two available alternatives, then, the three tasks are proposed to the volunteer in casual order, as follows:

- Presentation of a fixation cross (30 s)
- Task 1 (neutral text/code snippet/programming exercise)
- Presentation of a fixation cross (30 s)
- Task 2 (neutral text/code snippet/programming exercise)
- Presentation of a fixation cross (30 s)
- Task 3 (neutral text/code snippet/programming exercise)

An entire run lasts 28 minutes maximum.

The entire experiment (task selection, timing and presentation) is managed by a software implemented in Matlab environment. During the code programming task volunteers work with Eclipse IDE.

D. Signal processing

EEG recordings were processed in MATLAB R2017b environment by means of the EEGLAB toolbox. Specifically, the EEG signals were filtered with a FIR pass-band filter in the frequency band 1-45 Hz, and then they were downsampled to 128 Hz.

Moreover, a personalized common average referencing (CAR) has been implemented and applied: the average of the standard 19 channels of 10-20 system has been computed and then subtracted from the entire set of 29 electrodes acquired. This is done in order to obtain a re-referencing based on a set of channels homogeneously distributed over the scalp. Indeed, the majority of the 29 channels acquired is distributed in the frontal region, and a CAR on the entire set of electrodes would have provided an unbalanced reference.

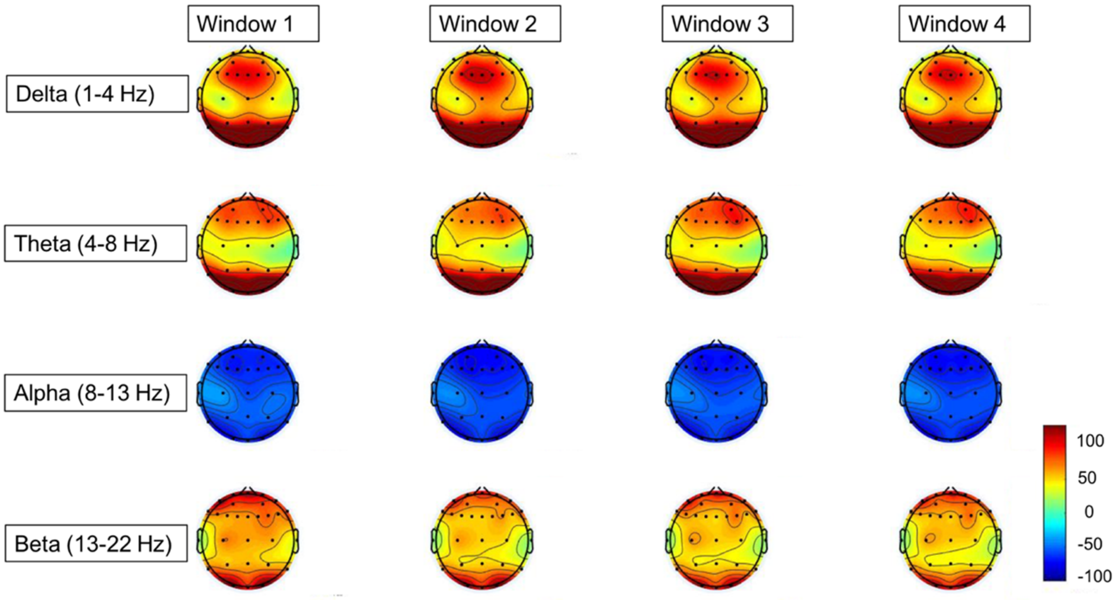

Fig. 1. Average topographical maps of the per cent variation of EEG power during the programming activity with respect to the baseline. Each row is related to a specific frequency band, while columns represent four time windows in which the signal has been divided

Noisy portions of the EEG traces were manually removed, while eye blinks and eventual artifactual sources were then identified and removed by means of the Independent Component Analysis (ICA) algorithm. EEG signals were finally normalized to zero mean and variance one.

For each EEG channel, power values corresponding to standard Delta (1-4 Hz), Theta (4-8 Hz), Alpha (8-13 Hz) and Beta (13-22 Hz) rhythms were computed. The EEG power spectrum was estimated on signal segments of 2-s length, with a 50% overlap. The power spectrum of each segment was obtained through the Welch's method.

Then, the time course of the variation (%) with respect to the baseline of the four EEG rhythms during the programming test was computed (1):

$$\Delta P_{prog,j}(i) = \frac{P_{prog,j}(i) - \bar{P}_{BS}}{\bar{P}_{BS}} \times 100 \quad (1)$$

Where, $P_{prog,j}(i)$ is the i-th power value in the j band during the programming phase, while $\bar{P}_{BS}$ is the average power in the j band during the baseline condition.

III. Results and Discussion

Topographical maps of the power in the four frequency bands for each time window averaged across the 10 subjects are presented in Fig.1. It can be noted that, passing from the baseline condition (typing on the keyboard with eyes closed) to a programming task, the power in Alpha band decreases and a general power increase in Delta, Theta and Beta bands in the frontal and parieto-occipital areas occurs.

Specifically, in order to evaluate the difference in the power content among the baseline and the four time windows, a repeated measures Friedman's test for each frequency band and for three cortical areas (frontal, central and parieto-occipital) was conducted. When opportune, a post-hoc analysis with Bonferroni correction (k=5) for pairwise comparisons has been performed. In all the frequency bands and in all cortical regions no significant differences emerged among the four time windows of the programming phase. Nevertheless, significant differences were generally observed between single time windows and the baseline phase (TABLE I). Specifically, Beta power increase is significant at the beginning of the task, while Delta and Theta intensification is significant even during successive phases of the task, especially in the frontal and parieto-occipital areas. Lastly, the decrease in alpha power is always significant, but in the first window for the frontal area.

The higher activation of frontal and parieto-occipital regions seems reasonable according to the specific task executed: the frontal region is known to be related to attentive processes, alertness, working memory and decision making [8, 9, 10], whereas the occipital lobe is involved in reading comprehension.

Indeed, code programming is a very complex task that involves phases of text reading, code analysis and comprehension, mathematic calculation, causal reasoning and decision making. Therefore, what we can see is a global behavior of the brain at the cortical level.

The power increase in Delta, Theta and Beta bands, instead, could be related to increasing attention and mental workload. Different studies, indeed, associated Theta rhythms with mental processes such as working memory, problem solving, and encoding [11, 12, 13]. Moreover, Theta oscillations have also been studied in relation to the increase of mental workload induced by working memory tasks [14].

Delta activity has been few investigated in relation to cognitive processes because the corresponding frequency band is frequently affected by artifacts. However, Harmony et al. observed an increase in Delta oscillations during the performance of mental tasks that require attention to internal processing. They suggest that this increase is due to an inhibition phenomenon, that consists in an optimization mechanism which suppresses 'useless' brain networks [15].

Beta rhythms, instead, has been largely investigated in relation to alertness and task engagement [16, 17]. The predominance of this activity in the first phases of the task can be due to a sudden increase of attention and alertness. Indeed, at the beginning of the task, the subject has to read and understand the instructions of the exercise and to decide how to implement the code. Then, processes of encoding and working memory could take place, associated with a decrease in alertness and an increase in mental workload, explaining the predominance of Theta and Delta rhythms.

As concerns the individual response observed in the 10 subjects, 2 of them showed a clearly visible theta peak in the power spectrum particularly pronounced on frontal and occipital electrodes (Fig. 2a). While other 2 subjects still present an alpha peak during the programming phase, even if less pronounced with respect to the baseline condition (Fig. 2b).

The described preliminary results must be further investigated. A better understanding should be reached by the integration of EEG-related informations with the other signals acquired, particularly with the NIRS, which allows to investigate deeper brain structures with respect to the EEG signal. Moreover, a functional connectivity analysis on the EEG signal will be carried out.

IV. CONCLUSIONS

The present study focused on the analysis of EEG signals acquired on ten experienced software developers during a programming task. From the spectral analysis of the EEG traces emerged that, passing from a baseline condition to a programming phase a significant increase in Delta and Theta activities on the frontal and parieto-occipital regions occurs. Moreover, at the beginning of the task a more spread activation in Beta band is observed. This evidence could be related to the involvement of the working memory processes and to the increase of mental workload. Nevertheless, these results suggest the need of further investigations. Specifically, the EEG signal will be integrated with other biological signals and information (e.g. eye-tracking) acquired during the programming task. Moreover, a functional connectivity analysis on the EEG traces will be conducted

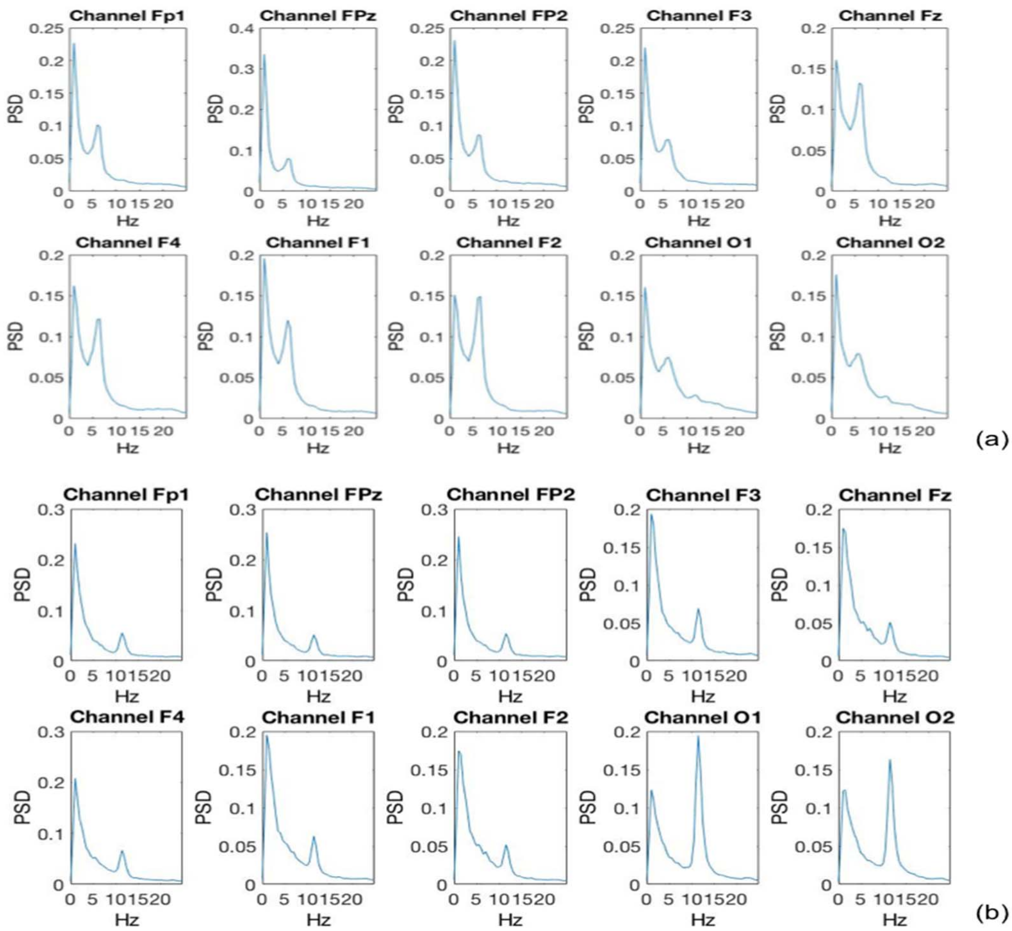

Fig. 2. (a) PSD on 10 channels of subject 7 related to the programming task. A peak in theta band on frontal electrodes and occipital can be observed. (b) PSD on 10 electrodes on subject 9 related to the programming task. A peak in alpha band can be observed on all electrodes.

TABLE I. Pairwise comparison results between the four time windows of the programming task and the baseline phase. Here is reported the p-value of the hypothesis test that the mean difference in frequency content between the considered time window of the programming activity and the baseline phase is zero. Significant values are indicated with * (p-value<0.05).

		Window 1-Baseline	Window 2-Baseline	Window 3-Baseline	Window 4-Baseline
DELTA	Frontal area	0.0468*⬆	0.0069*⬆	0.1091	0.1091
	Central area	0.3389	0.0013*⬆	0.1091	0.3389
	Parieto-Occ. area	0.0041*⬆	0.0013*⬆	0.0298*⬆	0.0186*⬆
THETA	Frontal area	0.0114*⬆	0.6599	0.0114*⬆	0.2365
	Central area	1	0.4771	1	1
	Parieto-Occ. area	0.0114*⬆	0.0721	0.0186*⬆	0.0298*⬆
ALPHA	Frontal area	0.4771	0.0002*⬇	0.0114*⬇	0.0008*⬇
	Central area	0.0298*⬇	0.0008*⬇	0.0298*⬇	0.0041*⬇
	Parieto-Occ. area	0.0298*⬇	0.0008*⬇	0.0069*⬇	0.0013*⬇
BETA	Frontal area	0.0024*⬆	0.6599	0.1091	0.1091
	Central area	0.0000*⬆	0.8969	0.1621	0.1621
	Parieto-Occ. area	0.0000*⬆	0.0041*⬆	0.1091	0.4771

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