Personalized Characterization of Sustained Attention/Vigilance in Healthy Children

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Abstract. Baseline shifts in electroencephalography (EEG) spectral response, in combination with phasic activity, can result in poor performance in sustaining attention. To explore the contribution of tonic response changes, we studied the 10 s segments preceding cues of correct and incorrect responses during target stimuli of an attention paradigm. The goal was to determine metrics that indicate tonic differences in spectral response between error and no error trials while performing a Sustained Attention to Response Task (SART) in a non-clinical setting. Data was recorded on 9 healthy children using IMEC's 8-channel wearable EEG headset with conductive polymer electrodes. In addition to fixed frequency bands, personalized bands based on individual alpha peak frequencies, were computed to account for inter-subject variability. The results indicate that relative theta and alpha power, along with their ratios, is a reliable metric indicating periods of attention or its lapses. The current results are a promising step towards understanding the cognitive responses of a healthy brain and potentially using them to assess the mental health of subjects undergoing training or treatment. Obtaining these results would not be possible without the use of a wireless dry electrode EEG headset, which demonstrates the essential role wearable devices have in monitoring cognition outside the clinical environment.

Keywords: Electroencephalography · SART · Sustained attention · Vigilance · Personalization · Children · Cognition

1 Introduction

Sustained attention/vigilance is defined as the ability to sustain conscious processing of random, repetitive stimuli without succumbing to habituation or distraction by other trivial stimuli. The ability to measure sustained attention/vigilance in response to events or tasks is essential in determining cognitive state and memory processes associated with the brain. Such objective means of measuring vigilance level is a vital step in the diagnosis and treatment of cognitive disorders that usually affect attention, learning or perception abilities in

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an individual. Several studies have investigated physiological correlates of attention, often comparing normal and population with cognitive disabilities [1–4], to determine whether these indices vary in different cognitive disease states. However, in order to understand the attention/inattention processes in a diseased population, it is essential to first understand a normal brain's response to sustained attention tasks in a daily life setting.

Researchers have explored a range of electroencephalography (EEG) features derived from data collected during experimental paradigms that involve cued responses to trials while anticipating a target stimulus. Orienting responses (phasic neurophysiological processes), which is described as the immediate, short-term response elucidated in the brain as a result of target stimulus, are often investigated to understand the cognitive processes related to attention. However, it has been reported that EEG changes cycle at lengths in the order of 15 s to minutes (i.e. tonic response) [5], which leads to the hypothesis that poor tonic activity, in combination to phasic processes, might result in poor task performance. Oken and colleagues [6] observed an increased slow frequency activity during decreasing attention and attenuation of alpha frequencies during maximal attention. In a series of investigations by Makeig and coworkers [7,8], poor performance was marked by relative increase in theta band power approximately 10 s prior to stimulus onset. The often encountered limitations in assessing these changes is the inter-subject variability of spectral responses, especially in children, since the alpha peak frequency matures progressively with age [9]. Moreover, these evaluations are performed in a clinical setting, which does not truly reflect the cognitive state in an uncontrolled environment where other external stimuli could dissolve the attention process. The fact the traditional EEG devices use wired systems limits the possibilities of conducting experiments that elucidate natural brain processes.

To determine whether sustained attention or its deficits can be distinguished in an uncontrolled environment, we designed a pilot study to assess the tonic spectral response while performing a sustained attention task. A random Sustained Attention to Response Task (SART) was chosen as the basis for the evaluation, due to its simple and straight-forward protocol in measuring attention. The original protocol, which involves displaying random digits between (1–9), was marginally modified. In order to keep the subjects engaged to the experiment, the numbers were replaced by pictures of cartoon characters as cues during the measurement. EEG data was collected from healthy children between 6–18 years age group while performing the modified SART. A wireless wearable EEG system, designed by IMEC, was used in the study as it allows unrestricted mobility to the subjects. Personalized frequency bands based on the individual alpha peak frequency (IAF), were evaluated in addition to traditional fixed frequency band definition of the EEG spectrum to investigate whether such means of normalization leads to comparable results among different subjects. The aim of the current evaluation was to determine whether metrics based on tonic responses during attention tasks can provide meaningful information about the cognitive state of an individual. The results might facilitate improvement in learning or treatment methods, either directly (interventions or neurofeedback training) or indirectly (treatment design), in treating cognitive impairments.

This report is organized as follows: Sect. 2 describes the study cohort, data acquisition, measurement protocol and data analysis methods used. The results of the experiment are presented in Sect. 3, following which Sect. 4 discusses the outcomes and inferences. Finally, the motivation and derived conclusions of the study are summarized in Sect. 5.

2 Materials and Methods

2.1 Subjects

9 children (Age range: 6–18 years; Mean $\pm$ s.d $=$ 12.44 $\pm$ 3.50 years; 3 male), without any history of neurological disorders participated in the study. Since the subjects were below 18 years of age, measurements were performed only after written informed consent was obtained from their parent/guardian. Two subjects (female) could not complete the data acquisition due to improper fitting of the headset and were, therefore, excluded from analyses. Two subjects (1 male and 1 female; 10 years) completed two measurements during different sessions, further described in the *Measurement Protocol* section.

2.2 Acquisition Setup

The measurements were performed using IMEC's 8-channel wearable wireless EEG headset, designed to be used in cognition and emotion research. The headset (shown in Fig. 1) is a highly integrated EEG acquisition device, with electrodes

Fig. 1. EEG headset designed by IMEC for cognition monitoring studies. Figures on the right show the polymer electrodes with silver/silver-chloride coating used for data acquisition.

positioned at Fz, F3, F7, F4, F8, P3, P4 and A1 of the International 10–20 electrode positioning system. Patient ground is placed at Pz and the reference electrode at A2 (right mastoid). This configuration allows re-referencing each of the channels to a specific reference (if required). The headset can be mounted easily, without the need of expert intervention, and is fitted with conductive polymer electrodes [10] coated with silver/silver-chloride layer on the tips, as shown in the figure. Each polymer electrode consisted of 15 pins of either 5 mm or 8 mm length. The small and large pin electrodes were attached to different electrode sites based on the morphology of subjects' scalp. The use of dry electrodes overcome the need for any skin preparation prior to use. Overall, the use of a wireless, dry electrode EEG system minimized setup time and made it possible for measurements to be performed in an uncontrolled setting. In addition, such wearable EEG devices allows for futuristic applications such as self-tracking or brain activity monitoring in daily life scenarios.

2.3 Measurement Protocol

SART, a GO/NO-GO paradigm, was chosen as the voluntary attention task to determine metrics for sustained attention. SART protocol is a computer-based user response task designed to measure a person's ability to withhold responses to infrequent and unpredictable target stimuli while responding as quickly and accurately as possible. Traditionally, the SART protocol involves flashing numbers between 1–9 on a screen for a short and fixed duration for which the user responds, depending on the type of cue (target or non-target stimulus). In order to motivate the young subjects of the current study, traditional SART was modified to include 8 pictures of cartoon characters instead of numbers. The cue duration, i.e. duration for which the cue appears on the screen, was set at 0.30 s for subjects between 6–12 years of age and at 0.15 s for older subjects. Inter-cue interval was between 1–1.5 s, inclusive of cue duration. Subjects were asked to respond to the cues by mouse button click for GO trials (non-target stimuli; probability of occurrence 87.5%) using the index finger of the dominant arm and refrain from producing any response when the NO-GO trials (target stimulus; probability of occurrence 12.5%) appeared. The picture that represented the NO-GO trial was shown to the subjects prior to the start of the measurement. The subjects were specifically instructed to give equal importance to accuracy and speed while performing the tasks. The protocol was implemented in the data acquisition software used to record EEG data from the headset. Timing information of cues and user responses (mouse button clicks) were recorded as events on the software. This information was later used for segmenting trials and determining correct and incorrect responses. Figure 2 summarizes a sample sequence of events during SART.

Each measurement session involved 300 cues appearing in random sequence. The current experiment design focuses on determining differences between *no error*, i.e. when subjects successfully inhibited response to NO-GO trials, and *error*, i.e. when subjects failed to inhibit a response to NO-GO trials. Since the

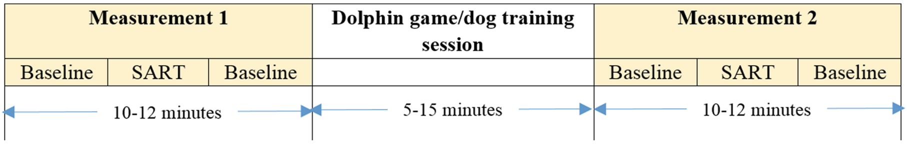

Fig. 2. Sequence of events during a measurement session.

NO-GO trials appeared only 12.5% of 300 trials, each subject performed two sets of measurements with a short break in between. Baseline recording, each comprising 90 s of eyes closed and eyes open recording, were performed prior to and after each SART measurement and were used to determine the IAF of each subject for personalization of frequency bands. During the break, the participants were divided into two groups, each of which participated either in a dolphin game or dog training session which lasted about 10 min. This activity was part of another evaluation and is not in the scope of the current study. The sequence of activities during the measurement sessions is described in Fig. 3. Participants were instructed not to remove the headset until the entire measurement phase was completed. Two subjects (1 male and 1 female) participated in both sessions and therefore recorded two sets of SART measurements. The measurements, including the inter-session activities, were performed under normal room conditions and is illustrated in Fig. 3. The protocol was approved by SAM foundation.

Fig. 3. Example acquisition setup during each measurement session

2.4 Data Analysis

Pre-processing: The pre-processing step involved band-pass filtering (3rd order Butterworth) in the 1–45 Hz frequency band and the use of 49–51 Hz notch filter (5th order Butterworth). Epochs of NO-GO trials starting 10 s prior to the cue and until the cue onset, were segmented based on cue timing information. An automatic artifact rejection method based on standard deviation and min-max of the signals within an epoch was used. By applying statistics based artifact rejection in the data analyses, epochs corrupted by noise and motion artifacts were rejected. After segmentation and artifact data exclusion, the epochs were classified as *no error* or *error* trials.

Feature Extraction: Power spectral densities were calculated using Welch method based on (i) fixed frequency bands and (ii) personalized frequency bands. The personalized frequency bands were computed based on methods described by Doppelymayr et al. [11], distributed around the IAF in order to account for the inter-subject variability. For personalization, the IAF was identified by analyzing 10 s epochs data from eyes closed baseline measurements. The spectral features were represented as both absolute and relative (ratio of power in specific frequency band to total power in the 1–30 Hz range) powers. The frequency bands for both feature extraction methods are described in Table 1. After spectral analyses, ratios between theta/alpha and theta/beta bands were computed for each channel.

Table 1. Definition of frequency bands during feature extraction. IAF corresponds to individual alpha peak frequency

Bands	Frequencies (Hz)	
	Fixed	Personalized
Theta	4–7.99	(0.4–0.6)*IAF
Alpha	8–12.99	(0.6–1.2)*IAF
Beta	13–29.99	1.2*IAF-29.99

3 Results

Non-parametric statistical tests were performed to establish differences since the distribution of each category and channel tested to be non-Gaussian (tested using one-sample Kolmogorov-Smirnov test). A significance level of 5% was chosen to determine whether the test agrees or rejects the null-hypotheses that both datasets come from the same population. The 1-tailed Mann-Whitney Wilcoxon (MWW) sign rank-sum tests revealed significant differences in relative theta power ($U = 20768.0$, $p = .009$) and alpha power ($p = .001$) in the frontal mid-line for fixed frequency bands. This contributed to the theta/alpha ratio ($p = 0.027$)

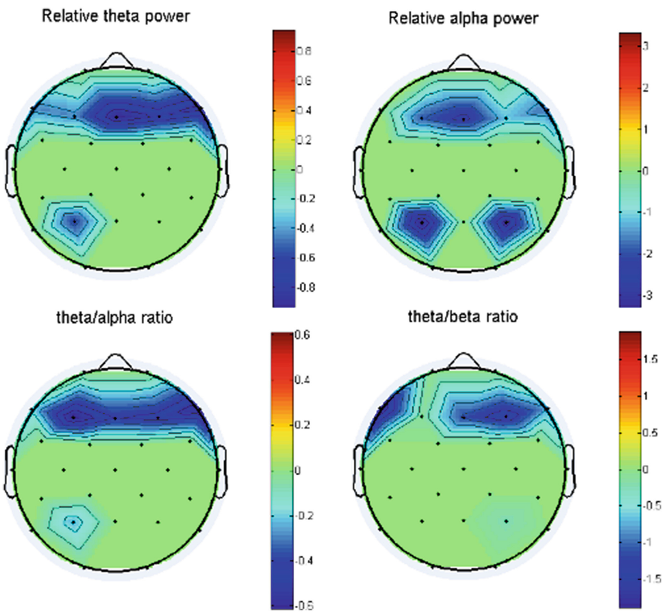

Fig. 4. Differences in fixed frequency bands' power distribution between *no error* and *error* trials.

and theta/beta ratio (p = 0.028) being significant indicators at the Fz channel. The personalized frequency bands revealed a significant difference in relative alpha power across the frontal positions of Fz (U = 20768.0, p = 0.024), F3 (U = 5742.0, p = 0.01) and F4 (U = 11040.0, p = 0.021) between the two test groups. Similarly, theta/alpha ratios were significant indicators of differences across the frontal electrodes (Fz: p = 0.001; F3: p = 0.007; F4: p = 0.009). Theta/beta ratio was significant for F3 (U = 5742.0, p = 0.005). Figures 4 and 5 represent the topographical power distribution for fixed and personalized frequency bands bands across different electrode positions.

4 Discussion

Several studies have focused on determining EEG spectrum correlates of attention deficit in cognitively challenged populations of different age groups [2,3,12]. Increased theta band power has been observed across ADHD subjects of all age categories during resting state [13–16]. This combined with the association of beta band activity to attentional arousal, implicates a high theta/beta ratio in frontal and central scalp regions in subjects with ADHD [12]. Reports by Ogrim et al. [17] suggests that an increase in theta band power and in turn, theta/beta ratio in ADHD population might be the result of inattention and executive problems rather than a direct manifestation of ADHD symptoms. However, the dynamics of band powers changes in ADHD is reported in the

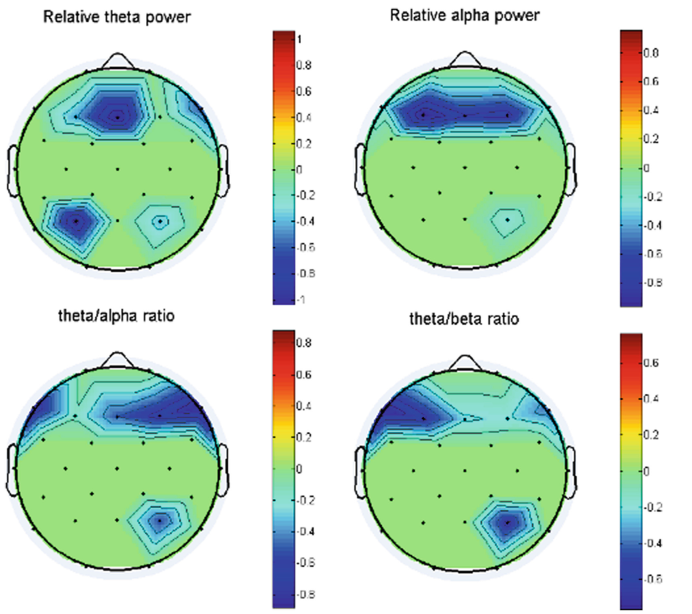

Fig. 5. Differences in personalized frequency bands' power distribution between *no error* and *error* trials.

resting state, unlike in normal subjects where differences were observed during lapses in attention while performing sustained attention tasks.

In order to understand the attention/inattention process in cognitively challenged population, it is essential to comprehend a normal brain's response to attention deficits. Several studies have focused on identifying event-related potentials (ERP) or response times correlates to attention tasks, but fail to address the contribution of baseline EEG in sustaining attention. The current study indicates that personalization of frequency bands, based on IAF, shifts the dominant frequency from beta to high alpha spectrum, thereby manifesting theta/alpha ratio as a marker for attention or its lapses. This is in line with reports by Dockree et al. [18], who performed dipole source analysis of alpha activity during fixed SART test on two subjects (Age range: 18–32 years), and reported that high tonic alpha power may be indicative of increased alertness towards task. In addition, under arousal or increased theta band power was observed in one or more of the frontal channels. Although this coincides with findings from subjects with ADHD, there is evidence to suggest that a similar increment in theta band power in frontal channels can be perceived during increased attentional loading [19]. The reason, both in the case of episodes of inattention in healthy subjects and pathophysiologies in ADHD, could be the result of under arousal marked by increased theta and decreased alpha activity in fronto-central regions of the scalp [12]. This is an interesting observation and calls for further exploration of personalized frequency bands.

Although the current study involved measurements during a static condition (i.e. attending to SART tasks in a seated position as shown in Fig. 3), other assessment or treatment modalities might require light to moderate movements, such as during animal interaction training which is commonly used in treating cognitive disabilities. The wireless headset design allows for data collection outside a clinical setting and use of polymer electrodes reduces the setup time and complexity. This is extremely beneficial, especially in studies involving children or cognitively impaired subjects, for whom adherence to stringent measurement protocols could prove challenging. By using sufficient signal cleansing mechanisms to exclude periods corrupted by motion artifacts, data from variety of protocols can be evaluated to determine attention lapses and in turn, learning/treatment efficacy. Moreover, the data visualization software can be run from a portable device making it easy to monitor personal cognitive state in real-time. This wearable solution opens new avenues in using EEG, such as monitoring attention lapses in children in a classroom, cognitive overload of air traffic controllers, etc.

5 Conclusion

This work demonstrates that a wearable and wireless EEG system can be used to monitor the brain activities while performing cognitive tasks in a regular classroom or home environment, providing a viable and convenient alternative to traditional gel-based systems. Moreover, the easy to *mount and monitor* headset provides a robust solution for performing brain signal analysis during different data acquisition protocols without any constraints on mobility or usability. To assess the attention level changes in healthy children, differences in spectral features computed for 10 s epochs preceding correct and incorrect SART trials were compared. The inter-individual differences in spectral response was accounted for by normalizing the frequency bands based on the IAF. The results have demonstrated that consistent differences in spectral power distribution can be observed between periods of sustained attention and its lapses. Although our evaluation has mainly focused on understanding the tonic responses as a result of attention lapses, it might be worthwhile to investigate phasic activity immediately prior to user response to identify similar metrics. Overall, the use of a wearable measurement system along with observations from the current study provide new avenues in assessing mental health or the effectiveness of therapy for subjects with cognitive disabilities.

The current study is unique in the aspect that cognitive functions evaluation was performed in a regular setting using a game-like protocol on healthy children. This combined with suitable intervention or neurofeedback training can be potentially used in a supervised environment for normal or cognitively impaired children alike, such that treatment is not bound to a clinical environment.

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