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Individualising EEG Frequency Bands for Sleep Deprivation Studies

Andreas Henelius, Jussi Korpela and Minna Huotilainen

Abstract— **A method for determining individualised frequency bands from electroencephalographic (EEG) power spectral density (PSD) plots is presented. EEG was collected during the performance of a computerised multitask test from 21 healthy male subjects, of which an experimental group of 14 subjects underwent sleep deprivation and 7 subjects formed the control group. EEG PSD plots were compared between the groups and were used to determine individual theta, alpha and beta bands for the subjects by studying the points of intersection between the individual subjects' normalised spectra and the normalised average spectrum of the control group. The results show that the frontal and occipital locations are best suited for the determination of individualised frequency bands. The proposed method can be used to enhance EEG spectral analysis of task-induced cognitive effort during sleep deprivation.**

I. INTRODUCTION

Work in the modern society has transitioned from involving physical workload to mental workload. The 24-hour society of today operates at a high pace, demanding constant attention from workers. Several professions require shift-work, in which it is common that workers suffer from sleep disturbances [1]. Almost half of the working population in Finland experiences at least some degree of sleep loss [2]. It is therefore especially important to study the impact of sleep deprivation on cognitive performance in safety-critical professions, where it is necessary to constantly maintain a high degree of vigilance. Previous research has shown that individuals respond differently to sleep loss, resulting in considerable differences in performance [3].

The electroencephalogram (EEG) is a widely used research tool in the investigation of cognitive processes [4]. The power spectral density (PSD) calculated from the EEG is used to assess the activity in different frequency bands. Studies have shown that alpha band activity is related to memory and information processing, and that alpha suppression occurs in situations involving mental effort [5], [6]. Decreases in alpha power also tend to occur together with increased theta activity [5]. In this study, it is thus hypothesised that subjects undergoing sleep deprivation will show suppressed alpha activity in comparison with a control group allowed to sleep normally, since the subjects in the experimental group will need to invest more effort in order to cope with the task demands than the subjects in the control group. The activity in the beta and theta bands is shown to increase with cognitive demand according to some studies [7], but the primary focus of this study will be on identifying features in the alpha band, since these are more easily distinguishable. The mental processes attributable to the theta and beta bands are also more diverse and therefore more challenging to take into account.

The generic frequency bands found in literature, however, are not optimal with regard to the phenomenon being studied. The bands are broad and there are several confounding factors complicating the spectral analysis. Examples of such factors are the combined effect of sleep deprivation and increased familiarity with the task, due to learning. It is also expected that the frequency bands show individual variation during the course of the experiment. In order to elucidate the features in the PSD due to cognitive effort in sleep deprivation, we need to locate and study the frequency bands that are maximally reactive to the studied effects, on an individual level. The PSD of the experimental group will be compared to that of the control group, thus isolating the effects of sleep deprivation, since all other factors except the daily amount of sleep are shared between the groups. This separates the method presented here from the standard method of determining the individual alpha frequency directly from the EEG PSD.

The aim of this study is to investigate the changes in EEG PSD in sleep deprived subjects during the performance of a computerised multitask test. In order to accomplish this, a method is implemented by which it is possible to identify individualised frequency bands (beta, alpha, theta) that best represent the variation in the EEG PSD.

II. METHODS

A. Subjects

The study group consisted of 21 healthy male subjects aged 23.6 ± 1.9 years (range 20–28). The subjects were randomly divided into two groups: an experimental group (N=14, subjects E01–E14) and a control group (N=7, subjects C01–C07). Subjects provided written informed consent.

B. Experimental Procedure

During the experiment, the subjects spent ten and a half consecutive days in the laboratory. The first two days of the stay were an adaptation day (AD), followed by a baseline day (BD). After this, the subjects in the experimental group underwent sleep restriction (SR) for five days (days SR_1 to SR_5, with the amount of sleep restricted to four hours. The SR days were followed by two recovery days (R_1 and R_2), during which the subjects were allowed to sleep for eight

All authors are with the Brain Work Research Centre,
Finnish Institute of Occupational Health, Helsinki, Finland.
Corresponding author: Andreas Henelius
Email: `andreas.henelius@ttl.fi`
Address: Finnish Institute of Occupational Health
Topeliuksenkatu 41 a A, 00250 Helsinki, Finland

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hours. The subjects in the control group were allowed to sleep for eight hours per night throughout the study. The experimental procedure has been described in detail in [8].

All subjects performed the Brain@Work computerised multitask test several times a day. In the test, the subject must simultaneously perform four tasks: an auditory response task (oddball paradigm), a mental arithmetic task, a memory task, and a visual vigilance task. The multitask test was used to simulate a cognitively demanding work-like situation. The EEG considered in this study was recorded during a 50-minute multitask session, that took place daily from about 14.30 to 15.20 in the afternoon.

C. Data Acquisition

EEG was recorded using the International 10–20 electrode setting system [9] from the following locations: F_{p1}–A_2, F_{p2}–A_1, C_3–A_2, C_4–A_1, O_1–A_2 and O_2–A_1. The recordings were made at a sampling rate of 200 Hz using an Embla A10 polysomnographic recorder (Medcare, Reykjavík, Iceland).

D. Data Analysis

The EEG signal processing was performed in Matlab R2010b (The MathWorks Inc., Natick, Massachusetts), using custom code utilising functions from EEGLAB [10]. Prior to PSD estimation, eye blinks were detected from the EEG signals. After this, the EEG signal was divided into 5-second calculation segments, with 50% overlap. The segments were processed using an amplitude rejection algorithm, and segments containing amplitudes above a threshold level of 150 µV or eye blinks were discarded. In each calculation segment, the PSD was estimated using Welch's method using a Hamming window and a Fast Fourier Transform (FFT) length of 512 samples, with 50% overlap. The final PSD was obtained as the median of all PSDs estimated for a particular channel. An example of a PSD obtained in this way is shown in Fig. 1, where the classic alpha band from 8–12 Hz is marked with vertical dashed lines. The average of each pair of channels in the opposite hemispheres was used as the final PSD for a particular front-back location, i.e., the PSD for the central location was obtained as the average of C_3–A_2 and C_4–A_1. In this way, three spectra were formed for each subject, here referred to as the frontal, central and occipital spectra.

1) Normalisation and Group Comparison: To facilitate inter-subject comparisons, the individual PSD of a particular sleep restriction day (days SR_1 to SR_5) was normalised by dividing the PSD at a certain frequency by the corresponding power in an individual baseline PSD at the same frequency, where the individual baseline PSD is defined as the median of the PSDs during days AD and BD. In group comparisons, the PSD for one subject on a particular day was compared against the group average of the PSDs of the control subjects, during the same day.

2) Determination of Individualised Frequency Bands: The normalised PSD was smoothed using a LOWESS-smoother (Locally Weighted Scatterplot Smoothing) to remove sporadic fluctuations and enhance the main features of the PSD. A window (6–15 Hz) containing the classic alpha band (8–12 Hz) was defined. Inside this window, the points of intersection between the normalised and smoothed subject spectrum and the normalised and smoothed group spectrum were detected (Fig. 2). If two points of intersection existed, the maximum vertical distance between the spectra of the subject and the control group was calculated, within the interval defined by the points of intersection. The individualised alpha band (vertical dashed lines in Fig. 2) was defined by the points of intersection. The individualised theta band was defined as the frequencies between 4 Hz and the lower endpoint of the alpha band, and the individualised beta band was defined as the frequencies between the higher endpoint of the alpha band and 30 Hz.

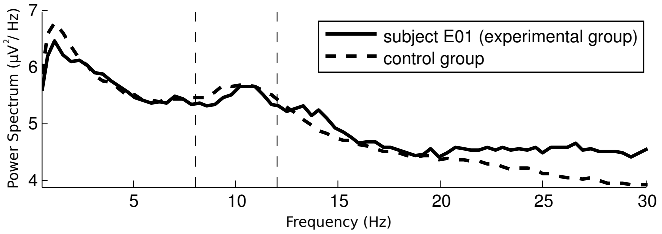

Fig. 1: PSDs calculated from the channel O_1–A_2 for subject E02 (solid line) and for the control group (dashed line) on day SR_5. The classic alpha band is marked with vertical dashed lines. Alpha activity is visible within this band.

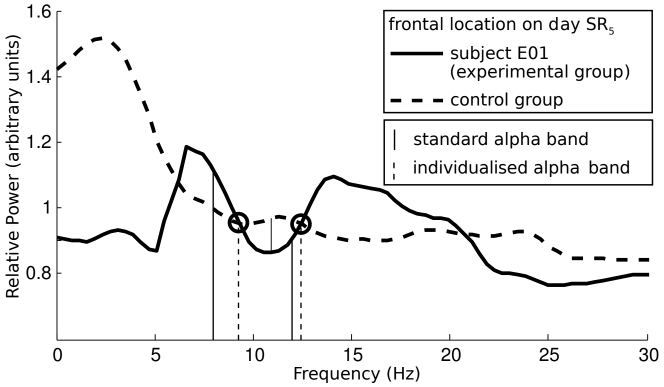

Fig. 2: Determination of Individualised Frequency bands.

The criteria for individualised alpha band determination were **(1)** two points of intersection and **(2)** the relative power in the subject PSD between the points of intersection was lower than the power in the control group PSD. The final individualised frequency bands were determined as the average of the bands calculated from the three channels, where possible.

III. RESULTS

A. Points of intersection

The points of intersection identified from the different locations on different days are shown in Table I, together with the total number of points of intersection identified

TABLE I: The number of points of intersection identified from the different locations on different sleep-deprived days, from all subjects in the experimental group.

Day	Frontal	Central	Occipital
SR_1	6	4	4
SR_2	6	2	5
SR_3	4	3	4
SR_4	5	4	7
SR_5	7	5	7
Total	28	18	27

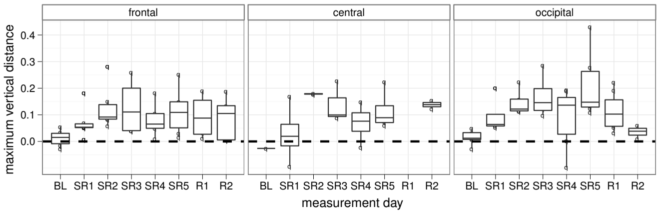

Fig. 3: Maximum vertical distance normalised with respect to values on day BL. One outlier (central location, subject E06, value -0.35) is not visible in the figure.

for each location. These points of intersection were used to determine the individualised theta, alpha and beta bands.

B. Maximum Vertical Distance

The relative change of alpha power, i.e., the maximum vertical distance, is shown in Fig. 3 on the different measurement days, for those measurements of the experimental group that fulfilled the criteria of individualised alpha band determination.

C. Individualised Frequency Bands

The individualised frequency bands were calculated separately for the three electrode locations for the subjects in the experimental group as the average over days SR_1 to SR_5. These bands are shown in Fig. 4. It was not possible to determine the bands in all situations.

The final average individualised frequency bands for every subject, determined as the average of the individual frequency bands obtained from the frontal, central and occipital locations are shown in Table II.

IV. DISCUSSION

A. Points of intersection

The points of intersection were easiest to determine from the frontal and occipital channels. It should be noted that even one point of intersection provides information in the determination of the individualised frequency bands.

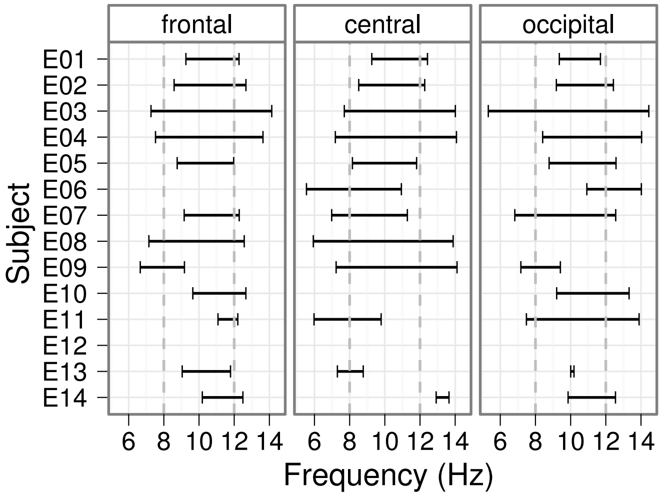

Fig. 4: Average individualised frequency bands. Dashed vertical lines represent the classic alpha band from 8–12 Hz.

TABLE II: Average individualised alpha frequency bands for subjects in the experimental group.

Subject	Start (Hz)	Stop (Hz)	Bandwidth
E01	9.31	12.02	2.72
E02	8.76	12.46	3.69
E03	7.09	14.15	7.06
E04	7.81	13.93	6.12
E05	8.59	12.14	3.55
E06	9.13	12.99	3.86
E07	8.02	12.21	4.19
E08	6.54	13.23	6.68
E09	7.01	10.12	3.11
E10	9.43	12.99	3.57
E11	9.03	12.37	3.33
E12	–	–	–
E13	8.78	10.25	1.47
E14	10.67	12.74	2.07
Mean	8.47	12.43	3.96

B. Maximum Vertical Distance

The results show that the maximum vertical distance describing alpha suppression increases with increased sleep deprivation (during days SR_1 to SR_5), and the alpha suppression decreases after the recovery days (R_1 and R_2). This is best observable in the frontal and occipital locations (Fig. 3). This is expected, since the observed alpha suppression is hypothesised to be due to the increased effort needed to sustain performance during sleep deprivation. As the subjects are allowed to sleep normally, the required effort for the same task will be less as compared to the sleep deprivation condition.

It is also possible that the control group shows increased alpha activity for instance due to the subjects becoming bored with the task, which was repeated several times a day. Thus, the observed effect could be a combination of alpha power decrease for the experimental group and alpha power increase for the control group. It should be noted that several of the subjects in the experimental group showed a clear reduction in alpha power compared to the control group in some conditions, but without points of intersection. Since such data did not meet the criteria for individual alpha band determination, it was left out from the analysis.

The maximum vertical distance on a an individual level can also be used as an indicator of a particular subject's proneness to the effects of sleep deprivation. A greater individual maximum vertical distance indicates that more effort is needed in the task performance. It should be noted that any comparison of the maximum vertical distance must be made relative to the subject's individual baseline, as was done in this study, using the subject as his or her own control.

C. Individualised Frequency Bands

The individualised frequency bands (Fig. 4) show that some subjects (e.g. E01, E02 and E05) fit quite well within the classic alpha band from 8–12 Hz, but the individualised frequency bands of most subjects are not entirely located within the classic band (e.g. subjects E03, E08 and E09). This means, that the proposed method allows the individual frequency bands to be fine-tuned with respect to the effects of sleep deprivation.

If EEG spectral analysis is performed by integrating the PSD, the individualised frequency bands probably allow the power to more accurately describe the individual responses to cognitive effort in sleep deprivation. If only standard alpha band power is used, it is possible that the effects would be either over- or underrepresented with respect to the control group, depending on the bandwidth of the individualised alpha frequency band. For instance, the power in the theta band (increasing power with increased mental effort) could leak into the alpha band (decreasing power with increased mental effort), thus possibly masking the effects of the mental effort. This, however, needs more research.

It would be interesting to study whether the individualised frequency bands shift during the course of the measurements. Taking this into account might allow even smaller differences in the PSDs to be investigated. Using the average frequency bands presented in this study it is, however, possible to achieve a better estimate than using the classic alpha band. The individualised frequency bands obtained using the method presented here may differ from those obtained by the common method of directly determining them from peaks in the PSD. The frequency bands obtained here represent the frequencies in the PSD where the differences due to sleep deprivation are the greatest, and therefore of most interest when comparing the cognitive performance of subjects in sleep deprivation.

The calculation of the individual frequency bands further supports the view that the frontal and occipital locations are best suited for the determination of individualised frequency bands. However, eyeblinks and eye movements affect the frontal locations more than the central and occipital ones, and it is therefore important to take this into account when performing the analysis.

Instead of using the FFT in spectral estimation, it could be possible to use autoregressive (AR) modelling. This would yield a parametrised spectrum that is smoother than the FFT-based, possible removing the need to separately smooth the PSDs in the analysis.

V. CONCLUSION

The EEG electrode locations most suitable for determination of the individualised frequency bands are the frontal and occipital locations. The signal from the channel pairs $\mathrm{F_{p1}}$–$\mathrm{A_2}$, $\mathrm{F_{p2}}$–$\mathrm{A_1}$ and $\mathrm{O_1}$–$\mathrm{A_2}$, $\mathrm{O_2}$–$\mathrm{A_1}$ were the most reliable in terms of showing a reduction of alpha power with increased sleep deprivation during a demanding cognitive test.

The use of individualised frequency bands is especially important when comparing PSDs using area measures reflecting alpha activity. The maximum vertical distance detected for the subjects could in the future be studied together with the subjects' task performance, thus providing information on the link between alpha suppression and task performance.

The stability of different the frequency bands over successive days needs further investigation, and this method should be applied to other sleep deprivation data sets including cognitively demanding task performance. Using the individualised frequency bands it is possible to accurately pinpoint the region of maximum variation in the PSD on an individual level. This allows a more accurate study of the effects of cognitive performance during sleep deprivation.

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