Which EEG Electrodes Should Be Considered for Alertness Assessment?

Agnieszka Wolska[1][a], Dariusz Sawicki[2][b], Marcin Kołodziej[2][c], Mariusz Wisełka[1][d] and Kamila Nowak[1]

[1]*Central Institute for Labour Protection - National Research Institute (CIOP-PIB), Warsaw, Poland*
[2]*Warsaw University of Technology, Institute of Theory of Electrical Engineering, Measurements and Information Systems, Warsaw, Poland*

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Abstract: The analysis of EEG signal is one of the objective methods used in alertness assessment. Many publications confirm the correct assessment of alertness level based on the analysis of selected brain waves. EEG registration is a difficult task; one of the important problems is the necessity to choose which EEG electrode to download the signal for analysis. The authors use different electrodes, often without justifying the choice. Equally often, the only justification is to say that the analyzed signal was the strongest among those available, or the least contaminated with artifacts. The aim of the article is to try to answer the question: signals which electrodes (channels) should be included in the alertness assessment. 33 participants took part in the experiment. Blue and red light was used to stimulate alertness. The impact of such light is documented in many publications. Alertness changes due to specific color of light were evaluated – the changes of alpha and beta bands were analyzed. Statistical analysis has shown that for alertness assessment the following electrodes should be considered: C3 and FC1 for alpha band and F3 and FP1 – for beta band signals.

1 INTRODUCTION

Apart from the visual response to light (light enables us to see), the non-visual response to light (melatonin suppression, core body temperature regulation, alertness and cognition, circadian clock changes) has been examined in detail since early 2000, when a new photoreceptor - intrinsically photosensitive retinal ganglion cell (ipRGc) containing the melanopsin had been discovered. The non-visual response depends on the light wavelength and intensity (irradiance level at the eye), time and duration of exposure. It was scientifically proven that light of particular wavelengths is able to affect human health, physiological and psychological behavior and wellbeing (Bellia et al., 2011, Wolska et al, 2018, Łaszewska et al., 2017, Sahin et al., 2014, Cajochen et al., 2005, 2007, 2010). Many studies confirmed that exposure to blue or red light increases the level of alertness (Figueiro et al., 2009, 2016, Figueiro & Rea, 2010, Plitnick et al., 2010, Sahin & Figueiro, 2013, Okamoto et al., 2014, Łaszewska et al., 2017, Scheuermaier et al, 2018, Iskra-Golec et al , 2017, Phipps-Nelson at al, 2009).

Maintaining a high level of alertness is a very important factor on many workstations, especially where the human error could result in occupational accident or threat to life or health of many people. The new knowledge of the dual role of light contributed in numerous studies concerning influence light on alertness level. Among the methods of objective alertness assessment, EEG signal analysis seems to be the most frequent used and relatively easy to use. From the EEG signal it is possible to differentiate bands: alpha (8-12 Hz), beta (13-30 Hz), delta (0.5-4 Hz), and theta (4.5-8 Hz) using fast Fourier transform. The EEG signal is closely related to the activity of the person. As the activity increases, the EEG shifts to higher dominating frequency and lower amplitude.

[a] https://orcid.org/0000-0003-3912-605X
[b] https://orcid.org/0000-0003-3990-0121
[c] https://orcid.org/0000-0003-2856-7298
[d] https://orcid.org/0000-0002-7145-6457

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(Malmivuo and Plonsey, 1995). In the awaking state (and with the eyes open) theta and alpha waves practically does not exist or their amplitudes are minimal (Sahin and Figueiro, 2013, Baek and Min, 2015, Klimesch, 2012, Okamoto, 2014, Sawicki et al., 2016). The increase of their amplitude in the awaking state is interpreted as the decrease of alertness and vice versa. Additionally sometimes beta, and delta bands are also taken into account in studies on alertness.

However, a unified or standardized method of analyzing the EEG signal for this purpose does not exist. The differences concern both the EEG registration (EEG equipment, number and placement of electrodes, type of electrodes etc.) and analysis of EEG signal for the alertness assessment (procedure of raw signal filtering – pre-processing, artifacts removing method, digital processing of cleaned signal, mathematical interpretation of recorded time series, spectral analysis, and selection of the electrodes for the analysis etc.). As it was mentioned before, for the purpose of assessing alertness after exposure to particular light usually two or three EEG bands are considered. Alpha, theta and beta (Lavoie et al., 2003, Figueiro et al., 2009, Plitnick et al., 2010, Sahin at al., 2013, Yokoi et al., 2003), alpha, theta and delta (Phipps-Nelson et al., 2009, Iskra-Golec et al., 2017), alpha and theta (Sawicki et al., 2016), alpha and beta (Scheuermaier et al., 2018). However some studies on vigilant attention and sleeping considered all bands and even for particular frequencies of those bands (Chellappa et al, 2017).

And even the same equipment for EEG registration and placement of electrodes according to the International 10-20 system is used and the same frequency ranges are analysed – the brain sites for analysis (what corresponds with particular electrodes placement on the scalp) are often different. Based on many studies on EEG registration for alertness level assessment some examples of electrodes sets could be specified:

- midline central: Fz, Cz, Pz and Oz (Łaszewska et al., 2017, Yokoi at al., 2003, Figueiro, 2009);
- motor cortex: C3 and C4 (Lavoie et al., 2003);
- frontal and occipital from midline central: Fz and Oz (Donskaya et al., 2012);
- anterior temporal lobes (T3, T4), parietal lobe (P3, P4), occipital lobe (O1, O2) (Phipps-Nelson et al.,2009);
- motor cortex (C3, C4), midline central (Fz, Cz, Pz and Oz) (Scheuermaier et al., 2018);
- motor cortex (C3, C4), parietal lobe (P3, P4), occipital lobe (O1, O2) and frontal lobe (F3, F4) (Chellappa et al., 2017);
- left frontal lobe (Fp1, F7, F3), right frontal lobe (Fp2, F4, F8), motor cortex (C3, Cz, C4), left temporal lobe (T3 , T5), right temporal lobe (T4, T6), anterior temporal lobes (T3, T4), posterior temporal lobes (T5, T6), parietal lobe (P3, Pz, P4), occipital lobe (O1, O2), and midline central (Fz, Cz, Pz) (Iskra-Golec et al., 2017).

Besides, sometimes the selection of electrodes is simply based on the strongest signal (the electrodes which provide the higher signal for particular band, regardless of their placement on the scalp). The significant effect of the registration channel (electrodes) on alpha, theta and beta power was stated by Figueiro (Figueiro et al., 2009). It means that electrodes selected for the final analysis could influence the interpretation of alertness. There is no knowledge about how the selection of particular electrodes influences the interpretation of alertness level based on particular bands of EEG signal. It would be interesting to find out which electrodes (channels) seem to be best correlated with changes of alertness level.

The aim of the article is to answer the question: is it possible to indicate EEG electrodes for signal processing and alertness interpretation based on alpha and beta bands in experiments with exposure to blue and red light? This paper presents the proposition of electrodes selection for alertness assessment based on results obtained during the study carried out using the 32 electrodes EEG registration with exposure to blue and red light.

2 EXPERIMENT

2.1 Participants

Thirty three right-handed male volunteers, aged 20-30 years (mean age 23,4, SD=2,12 years) participated in the study: 17 of extreme morning chronotype and 16 of extreme evening chronotype, identified using *Composite Scale of Morningness* – CSM (Smith et al., 1989, Jankowski, 2015). All participants were paid and the following exclusion criteria were applied: sleep or mental health problems, color blindness, glasses to work with a computer. The experimental protocol was reviewed and approved by the Senate Committee of Research Ethics of Józef Piłsudski University of Physical Education in Warsaw. Informed written consent was obtained from each participant.

2.2 Light Exposure

The experiment was conducted in a windowless, air-conditioned laboratory room of white walls, with general indirect white LED lighting operated by lighting control system. The general lighting was used for dim light conditions i.e. < 5 lx at the eyes. Additionally two desk LED luminaires, specially designed for exposure to blue and red light, were positioned, according to Alkozei et al. (Alkozei et al., 2016), at 80 cm distance from the participant's nasion, with each light cantered at a 45 degree angle from midline. The established illuminance level for exposure was 40 lx both for red (630 nm) and blue light (465 nm). The technical aspects of light exposure are provided in (Wolska et al., 2018). The study was carried out during the winter season.

2.3 Procedure

The experimental session started respectively at 7:30 am for morning chronotype and at 11:00 am for evening chronotype, similarly to study of Maierova (Maierova et al., 2016). The subjects were asked to maintain a fixed regular plan sleep, lasting at least 7 hours during the week preceding the start of the experiment. Every participant took part in two experiments, each with exposure to different light. The session order was counterbalanced for each individual, to avoid the impact of familiarizing with the procedure on results. One week interval between the experiments was established (Wolska et al., 2018). During each experiment participants underwent 30 min under dim light (< 5 lx), 20 min behavioral tests with EEG registration (Resting 1, GoNoGo 1 and n-back 1), 30 min under blue or red light exposure (no tests and EEG registration performed), 70 min behavioral tests with EEG registration (Resting 2, GoNoGo 2, n-back 2, GoNoGo 3, n-back 3, GoNoGo 4, n-back 4, Resting 3). All EEG registrations were performed under dim-light. The resting state (plus symbol ("+") presented on the screen for 3 minutes together with EEG registration) was executed three times:

(1) after dim light and just before exposure to blue or red light,
(2) just after exposure to particular light (acute alerting effect) and
(3) 70 minutes after exposure (sustained acute alerting effect).

2.4 EEG Registration

EEG measurements were taken using 256- channel g.Hlamp amplifier (Guger Technologies, Graz, Austria). Signal was recorded from 32 electrodes paced according to the 10-20 International system (Figure 1). All impedances were kept below 30kΩ during the whole recording session. A Simulink model (running under Matlab 2014a) was used to control the registration of the signal. It consisted of the building block provided by the manufacturer of the system (Guger Technologies, Graz, Austria) (Wolska et al., 2018).

3 DATA ANALYSIS

EEG recordings were taken from 32 electrodes and then analyzed in order to assess the changes in alertness level: "short term": before exposure (1) and after exposure to light (2), "long term": before exposure (1) and after exposure (3). This article focused on changes for alpha and beta frequency bands on all 32 electrodes – the layout in Figure 1. The alertness level assessment based on changes in energy in alpha and beta bands is based on the following assumptions: the higher energy in alpha band the lower level of alertness, the higher energy in beta band the higher alertness level.

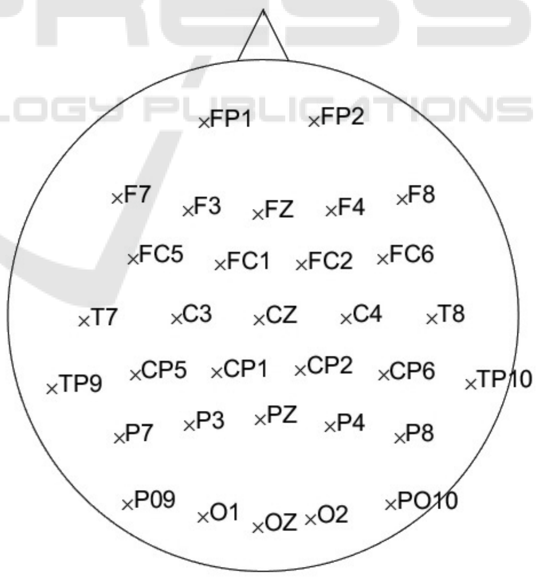


Figure 1: The layout of 32 electrodes used in the experiment.

3.1 Preprocessing

The EEG recordings were filtered using the same processing method for each registration. Band pass FIR filtration was applied in order to eliminate frequencies higher than 32 Hz and lower than 0.01 Hz for all 32 channels. This had been done to ensure that neither occasional electrical grid impact and higher frequencies harmonics nor low frequencies events are included in signal. Furthermore recordings were visually checked for artifacts (due to blinking, movements etc.) and manually marked and removed. In case of presence of multiple artifacts in signal interpolation (based on 2 neighboring – closest channels) was applied. Maximum of 4 channels were interpolated and in case of 5 or more channels significantly affected by artifacts data set was marked as rejected from further analysis. At the end Infinite Component Analysis (ICA) was performed for each data set individually. After filtration each data set was analyzed.

3.2 Feature Extraction

The initially prepared signal was digitally processed. To remove signals outside the alpha and beta bands and then estimate the energy in those bands, a 4th order lowpass Butterworth filter was applied. Afterwards signal was divided into 5 seconds windows. The number of windows depended on the correctly recorded registration time (after artifacts removal). As a result, 9 to 30 5-second windows were obtained, which corresponds to obtaining 9 to 30 element sample sets for individual bands (alpha and beta). For each window of signal the energy was calculated using the variance calculation – this way power analysis was performed. This digital processing procedure was applied for each participant, for each electrode of the recorded signal and for interaction with two colours of light (red and blue). Considering the fact, that:

- three independent signal registrations were carried out (resting state (1), (2) and (3)) for each experimental session,
- 33 subjects were examined (morning chronotype – with assigned codes: R01 - R17, evening chronotype – with assigned codes: W01 - W16),
- the interaction of two color of light was used,
- signal was registered on 32 electrodes,
- EEG signal energy was calculated in two independent alpha and beta bands,

3x33x2x32x2=12672 sets of 9 to 30 element signal samples were obtained.

3.3 Statistical Analysis

The energy samples sets were subjected to further statistical analysis. For each set of samples (before exposure (1), after exposure (2) and after exposure (3)) the mean values of energy (M1, M2, M3) and standard deviation (STD1, STD2, STD3) were calculated. Statistics were calculated using the Student's t-test. The Student's t-test compares pairs of sets between different registrations. Two types of comparisons were made: between the registration of resting 1 (R1) and 2 (R2) and between the registrations resting 1 (R1) and 3 (R3) - marked as R12 and R13 respectively. The null hypothesis H0 was assumed that the means in the compared sets of signal samples of the analyzed resting states do not differ statistically significant (no effect of light on energy values) and the alternative hypothesis Ha, that the means in the compared sets of samples differ significantly (effect of light on energy values). The significance level of rejecting the null hypothesis was assumed as α=0.1. If the value of the test statistic (Student's t-value) falls in the rejection region the null hypothesis H0 is rejected in favor of the alternative hypothesis Ha. The statistical analysis was carried out using the Matlab environment (2018a). The built-in functions mean, std, ttest2 were used for statistical calculations.

An exemplary set of results for testing the mean energy values of a resting signal for one electrode Oz is presented in Table 1. Taking into account the results of Student's t-tests, a “resultant” measure of significance of a given difference (H12: between (1) and (2), H13: between (1) and (3)) was introduced. The following values for that measure were assumed: 1 – statistically significant difference, 0 – not significant difference. T12, T13 are the values of t-Student’s statistics t, p12, p13 are the statistical significances.

The results of the sum of measures H12 and H13 (assigned as HS12 and HS13) indicate that after exposure to blue light there were statistically significant changes in energy recorded on the electrode Oz between resting state (R1) and (R2) in 9 subjects and between resting state (R1) and (R3) in 10 subjects with evening chronotype.

The above presented analysis allows selecting the electrodes on which the energy differences statistically significant in the alpha or beta bands between the R12 and R13 resting states occured most often. For this purpose, for each electrode, for each band and each difference (R12 and R13) a sum of “resultant” measures of significance H12 and H13 was calculated (as HS12 and HS13 respectively) and presented in Table 1. The higher the measure HS12 or HS13 of the individual electrode, the more the differences in the energy of the analyzed signals of a given electrode were statistically significant. Because

Table 1: An exemplary set of energy results obtained for the Oz electrode and alpha band (evening chronotype W and blue light N). M1, M2, M3 – the value of energy in [□V^2]. STD1, STD2, STD3 – standard deviations. T12, T13 are the values of t-Student's statistics t, p12, p13 are the statistical significances. The significance level of rejecting the null hypothesis was assumed as α=0.1. If p12<α , H12=1, otherwise H12=0, for p13 and H13 in the same way.

Subject	H12	H13	M1	M2	M3	STD1	STD2	STD3	T12	T13	p12	p13
W01N	0	1	2.575	69.132	0.879	0.703	301.779	0.223	-1.011	10.298	0.318	0.001
W02N	1	1	1.812	2.459	1.612	0.392	1.812	0.231	-1.780	1.748	0.081	0.089
W03N	1	1	1.472	2.163	2.245	0.340	0.523	0.428	-5.779	-6.509	0.000	0.001
W04N	0	1	65.068	59.924	40.203	21.023	15.757	24.512	0.959	3.433	0.343	0.001
W05N	0	0	11.046	15.037	9.535	4.743	12.679	2.744	-1.271	1.240	0.211	0.223
W06N	1	1	15.398	11.023	11.689	3.855	3.330	3.553	4.285	3.779	0.000	0.000
W07N	1	0	1.508	3.239	1.494	0.369	1.021	0.333	-7.877	0.142	0.000	0.888
W08N	1	1	7.496	11.464	4.779	2.152	3.984	1.339	-4.639	5.462	0.000	0.001
W09N	1	0	29.627	20.426	22.842	15.384	8.437	8.974	2.582	1.660	0.013	0.104
W10N	0	0	3.154	2.992	3.052	0.802	0.690	1.420	0.667	0.329	0.508	0.743
W11N	1	0	2.073	2.434	2.256	0.380	0.682	0.305	-2.230	-1.302	0.031	0.202
W12N	1	1	46.288	60.325	61.529	12.119	16.229	14.805	-3.155	-3.916	0.003	0.001
W13N	0	1	3.855	3.292	5.616	1.983	0.687	2.340	0.866	-2.640	0.394	0.012
W15N	0	1	6.737	5.940	14.288	3.418	3.874	7.502	0.726	-4.695	0.472	0.001
W16N	1	1	5.834	4.705	3.087	2.477	2.085	1.242	1.794	5.103	0.079	0.001
Sum	HS12=9	HS13=10	-									

the analyzed differences R12 and R13 are associated with stimulation of light of a specific color, the analysis allows selecting the electrodes on which the response to stimulation with a specific color is the strongest.

4 RESULTS AND DISCUSSION

The influence of blue and red light on energy significant changes in alpha and beta bands was observed. Only statistically significant cases of the influence of light on energy were analyzed. It is worth noting that the significance of the interaction of light with signals from specific electrodes was confirmed by the Student's t-test in all considered groups, i.e.: the interaction of blue light (N) in the morning and evening chronotype, the interaction of red light (C) in the morning (R) and evening (W) chronotype. The number of cases of significant changes in energy (both between R12 and R13 resting states) on individual electrodes in alpha and beta band is presented in Table 2. The highest values of HS12+HS13 measure were marked in red color (for red light exposure) and blue color (for blue light exposure) in Table 2. Also the electrodes for which the highest values of that measure were found have been marked in green color (for alpha band) and in violet color (for beta band).

The difference between signal channels (electrodes) response to blue and red color in alpha and beta bands has been found. The visualizations of the number of significant differences (HS12 + HS13) in alpha and beta bands on a scalp are shown as the impact maps in Figure 2 after blue light exposure and in Figure 3 after red light. When analyzing impact maps for both chronotype groups, it should be noted that these maps are different. This means that it is difficult to indicate one universal electrode for all groups.

The impact maps presented in Figures 2 and 3 are clearly asymmetrical. The maximum HS12+HS13 for alpha bands (both for red and blue light) is shifted from the central midline to the left motor cortex area.

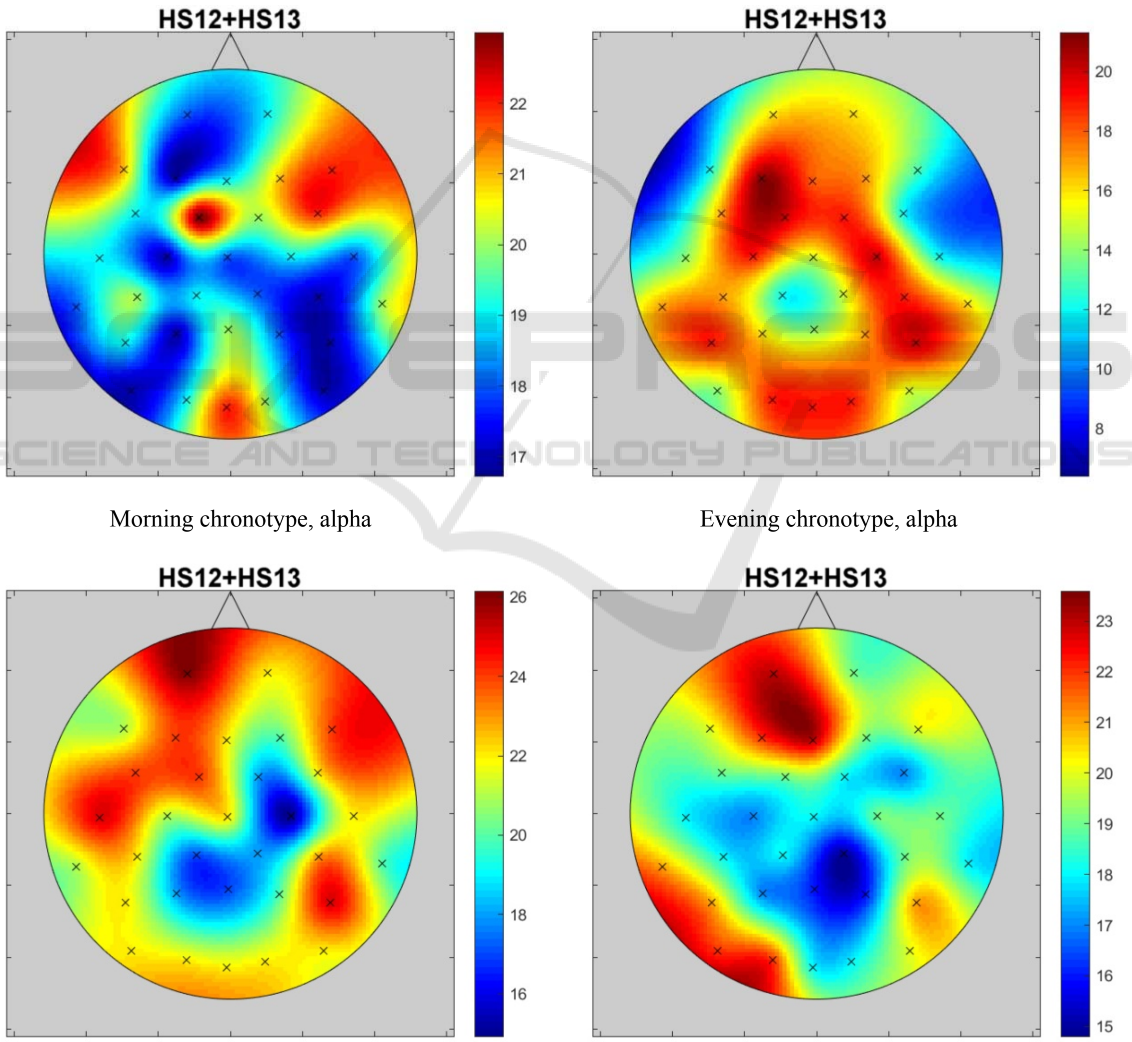
Table 2: The sum of HS12 and HS13 measures for individual electrodes for both color lights stimulation among evening and morning chronotypes, and for the whole group. The highest values of HS12+HS13 measure were marked in red color (for red light exposure) and blue color (for blue light exposure). The electrodes for which the highest values of that measure were found have been marked in green color (for alpha band) and in violet color (for beta band).

Electrode	HS12+HS13											
	Alpha band						Beta band					
	Morning chronotype		Evening chronotype		Morning+evening chronotype		Morning chronotype		Evening chronotype		Morning+evening chronotype	
	Red light	Blue light	Red light	Blue light	Red light	Blue light	Red light	Blue light	Red light	Blue light	Red light	Blue light
C3	**22**	17	**21**	19	**43**	36	17	21	21	17	38	38
C4	20	19	19	20	39	39	12	15	19	19	31	34
CP1	19	19	18	12	37	31	20	17	22	18	42	35
CP2	18	18	18	15	36	33	16	18	16	15	32	33
CP5	17	20	19	17	36	37	**19**	22	**26**	18	**45**	40
CP6	19	17	20	19	39	36	19	23	20	19	39	42
CZ	21	18	14	15	35	33	20	22	19	18	39	40
F3	19	17	17	21	36	38	**23**	**24**	**22**	**22**	**45**	**46**
F4	20	21	17	17	37	38	17	20	21	19	38	39
F7	17	21	18	12	35	33	19	21	20	20	39	41
F8	22	22	17	13	39	35	18	24	24	20	42	44
FC1	17	**23**	17	**20**	34	**43**	16	24	18	19	34	43
FC2	21	20	15	19	36	39	16	18	18	18	34	36
FC5	17	19	16	17	33	36	22	24	18	19	40	43
FC6	21	22	16	12	37	34	**22**	22	**24**	17	**46**	39
FP1	16	18	18	16	34	34	**21**	**26**	**25**	**23**	**46**	**49**
FP2	14	19	16	16	30	35	17	22	22	19	39	41
FZ	19	19	19	18	38	37	15	22	18	23	33	45
O1	15	19	20	19	35	38	19	22	16	22	35	44
O2	16	20	15	19	31	39	16	22	18	18	34	40
OZ	17	**22**	15	**19**	32	**41**	18	22	19	18	37	40
P3	18	17	17	16	35	33	18	18	17	17	35	35
P4	18	18	16	17	34	35	15	20	19	16	34	36
P7	**21**	19	**19**	19	**40**	38	22	22	19	21	41	43
P8	18	17	16	20	34	37	19	**25**	17	**21**	36	**46**
P09	17	17	18	14	35	31	20	22	23	22	43	44
PO10	17	17	17	15	34	32	24	22	18	20	42	42
PZ	18	20	15	14	33	34	15	17	16	16	31	33
T7	16	19	14	14	30	33	24	25	19	18	43	43
T8	15	18	21	12	36	30	**22**	22	**23**	19	**45**	41
TP9	18	18	18	17	36	35	22	21	20	21	42	42
TP10	20	20	18	16	38	36	21	20	19	18	40	38

All participants in the study were right-handed. However, it is difficult to draw conclusions about lateralization of brain function influence on the brain wave effects, although statistically confirmed cases are considered. There were no studies carried out on a group of left-handed. However, this indicates the need to continue research with particular emphasis on this aspect.

Considering the influence of visual stimuli on alpha waves, O1 and O2 electrodes are often indicated as the most appropriate for recording such waves. In none of the presented results has this been confirmed. Moreover, both for W and R chronotypes and red light, and R chronotype and blue light, the O1 and O2 electrodes were those where the values of HS12+HS13 measure were relatively small. Only in the case of W chronotype and blue light exposure values of that measure were above average.

Analyzing the presented results it would be possible to propose the use of C3 electrode to assess the interaction of red light and the FC1 electrode to assess the interaction with blue light. These electrodes are located very close together on the scalp. Perhaps a good solution would be to use the average signal from electrodes C3 and FC1 for alertness assessment with blue light interaction. It would be worthwhile to continue the tests by analyzing the signals of other electrodes in this area (C3, FC1). An interesting solution would be to take



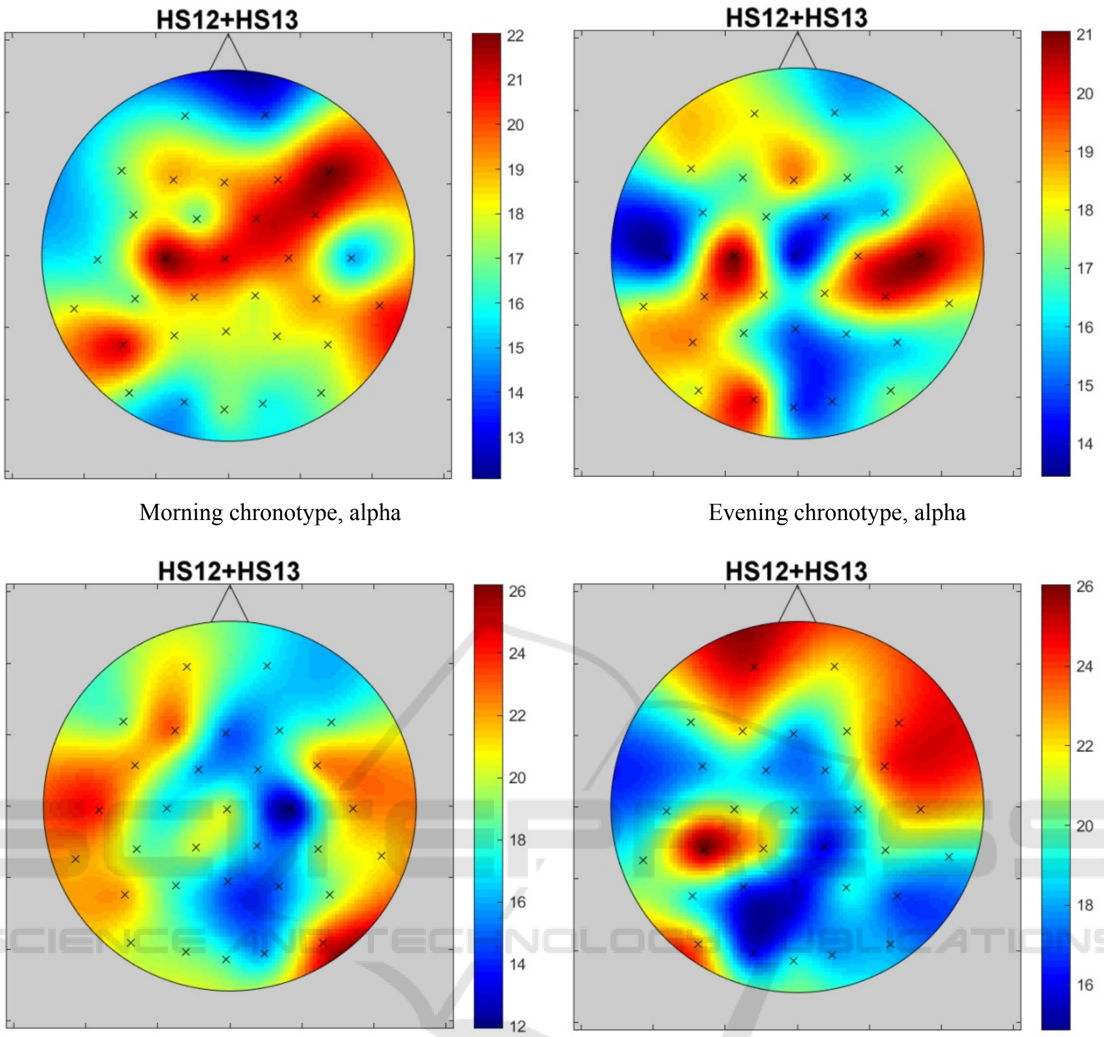
Morning chronotype, alpha

Evening chronotype, alpha

Morning chronotype, beta

Evening chronotype, beta

Figure 2: The distribution of significant differences (HS12 + HS13) number in alpha and beta bands on a scalp after exposure.



Morning chronotype, alpha

Evening chronotype, alpha

Morning chronotype, beta

Evening chronotype, beta

Figure 3: The distribution of significant differences (HS12 + HS13) number in alpha and beta bands on a scalp after exposure to red light.

into account the signals from the EEG registration with a larger number of electrodes.

Beta band is less frequently used in alertness analysis based on EEG registration. However, the analysis of the presented results shows that the maximum of significance measures HS12+HS13 for beta waves on specific electrodes are higher than the for alpha band. For beta waves, the electrodes from the area around central midline do not give high HS12+HS13 and thus seems not to be the best to the alertness analysis caused by different colors of light. The highest significance measures HS12+HS13 were noted for the electrodes at the area of left frontal lobe (F3 and FP1), both for red and blue light. That's why it seems reasonable to propose the use of F3 and FP1 electrodes to assess the interaction of red light and blue light. HS12+HS13 on these electrodes are the highest for all participants (both R and W chronotype) and for interaction with red and blue light.

5 CONCLUSIONS

The conducted study has shown that electrodes can be selected to assess alertness on the basis of EEG signal analysis. In the current research, the researchers used different approaches to the selection of electrodes. Reasonable reasons are signal strength or its purity (no interference or artifacts). However, signals not on all electrodes are equally related to the effect of light on alertness. It is worth attempting to additional signal clearing in a situation where we can use an electrode that collects brain waves from the area strongly associated with the impact of the appropriate stimulus. Research has shown that the selection of electrodes can be made in a way that gives a higher statistical significance of the impact. At the same time, it is worth paying attention to the fact, that presented in this article study is one of the first studies of this type (if not the first one at all). Similar research should be continued.

It is worth analyzing others, additional factors that can affect the significance of the interaction - and thus the selection of electrodes for signal analysis. In the presented study, the extreme chronotypes were taken into account. It turned out that this has a significant impact - the interaction maps for different chronotypes are different (Figures 3 and 4). Only right-handed participants took part in the study. It seems that from the point of view of the slightly different functioning of the brain dependent on lateralization, this is one of those factors that is worth additional research. Attention should be paid to the fact that while the influence of blue light on alertness is documented in many articles, the influence of red light is confirmed in a much smaller number of publications. This is mainly due to the well-documented impact of melatonin level on alertness and the documented ability to influence light on melatonin production.

The study described here shows that the effect on brain waves of blue and red light is similar. What once again confirms the possibility of interaction with red light on alertness, although through a mechanism other than melatonin production control.

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