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The sensitivity of EEG waves in discriminating the complexity of psychomotor tasks

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Abstract: Previous research has shown that changes in the spectral power of the alpha, beta and theta rhythms can be a good indicator of the load caused by performing different types of cognitive and psychomotor tasks. In this study, neural activity was recorded while performing the Fitts' Tapping Tasks, a kind of psychomotor tasks. These tasks were used since their difficulty is objectively quantified and expressed in bits. The tasks used had difficulty levels of 2, 4 and 6 bits. The aim of the study was to determine how sensitive the changes in the power spectrum of the three frequency bands is in relation to changes in task difficulty. 35 participants between the ages of 19 and 22 took part in the study. All participants were right-handed and had no neurological diagnoses. During the performance of the tasks, the EEG was recorded, as well as electrooculography (EOG). The EEG was also recorded during the resting phase, in which the subjects sat with their eyes open. The electrodes for EEG recording were placed at the following positions: F3, F4, FC3, FC4, C3, C4, CP3, CP4, P3, P4, Fz, FC, Cz. The results showed that all three frequency ranges (α, β and θ) were able to distinguish periods of task performance from periods of rest, since spectral powers were different for different conditions. Changes in the alpha power were found in the parietal area, while changes in the beta and theta rhythms were dispersed. A change in task difficulty led to changes in the power of the beta rhythm, but not of the alpha and theta rhythms. With increasing task difficulty, the power of the beta rhythm increased in all used electrode positions, but these changes are not linear, as there is a difference when comparisons are made for tasks of 2 and 6 bits, and 4 and 6 bits, but not for 2 and 4 bits. These changes were interpreted as a consequence of an increase in cognitive load.

Key words: EEG, alpha, beta, theta, Fitts' Tapping Tasks

INTRODUCTION

Electroencephalography, in which the summed electrical activity of populations of pyramidal cells is recorded (Beres, 2017), is a widely used technique in both clinical practice and scientific research. There are several reasons that make the use of this technique attractive. It is a non-invasive technique that causes no discomfort to the subject/patient. In addition, the development of biomedical technology is progressing very rapidly, making these devices more compact and easier to handle, and at the same time more financially accessible (Nikolić Ivanišević, 2020). The technique has excellent temporal resolution, as changes in the brain due to a change in behavior can be recorded after less than a millisecond (Lystard & Pollard, 2009). The spatial resolution is poorer compared to other non-invasive brain imaging techniques (e.g. functional magnetic resonance imaging - fMRI) (Babiloni et al., 2001), as the electrodes placed on the skull do not record the potentials that originate directly under the electrode, but their source may be far away from their position. Despite the lack of spatial resolution, EEG is still more commonly used (at least in a research context) compared to other non-invasive imaging techniques, as they also have some disadvantages (e.g. low temporal resolution, they are not as easily accessible to researchers, they are limited in performing certain tasks during recording, etc.).

Among the many ways in which EEG can be used for research purposes, some of the research relates to the assessment of mental or cognitive load during the performance of various tasks. Cognitive load is a fundamental concept in the study of human performance. It is a measure of the mental effort required to complete a task, and the high demand on our cognitive resources can lead to cognitive overload. As a result, fatigue and stress occur (Yoo et al., 2023). Studies that have used EEG to assess cognitive load have typically used tasks that assess working memory and attention (e.g. Klimesch, 1999), multitasking (e.g. Wickens & Gutzwiller, 2017), vigilance (Gorgoni et al., 2014) and more recently tasks that have greater ecological validity because they simulate, for example, driving a car (di Flumeri et al., 2018). These studies aimed to look for changes in the representation or spectral power of specific types of EEG waves. The types of EEG waves are defined by their amplitude, frequency, location, symmetry and reactivity (Parvizi, 2018). When classifying the waves, the frequency is taken into account and we distinguish: delta (0.5 - 4 Hz), theta (4 - 7 Hz), alpha (8-12 Hz), beta (13-30 Hz) and gamma (30-80 Hz) waves.

To answer the question of what previous research has shown regarding the spectral power of specific wave types or frequency ranges in *relation to cognitive load*, Chikhi et al. (2022) conducted a meta-analysis in which they eventually included 24 studies. The initial number after the database search indicated a large number of available sources (5 716), but the authors conducted a rigorous selection regarding the criteria for inclusion of research and eventually arrived at 24 studies. After reviewing the literature and analyzing the data available in the papers, they concluded that changes in cognitive load are associated with changes in spectral power in three frequency ranges: *alpha, beta and theta waves*, with changes in theta power, particularly in the frontal region, being recognized as the best index of cognitive load. The direction of changes in this frequency range is such that *theta* synchronization occurs with increasing workload, i.e. theta power is significantly higher under conditions of high workload than theta power under low workload. Alpha and beta rhythm power have also been recognized as parameters that differentiate workload, but the relationship between spectral power and workload level is less straightforward. The meta-analysis (Chikhi et al., 2022) showed that alpha power decreases with increasing workload. There are many sources in the literature that confirm that the presence of the *alpha* rhythm is lower in situations of higher cognitive load (Basar et al., 2001; Hanslmayr, 2012; Klimesch, 1999). However, in relation to this frequency range, it is also important to note some inconsistencies in the literature relating to the opposite direction of change, i.e. an increase in posterior alpha power as a function of increasing cognitive load (e.g. Jensen et al., 2002; Tuladhar et al., 2012). A possible explanation for this "paradoxical" finding is offered by the author van Ede (2018), according to whom alpha desynchronization occurs when working memory tasks are used to assess cognitive load and verbal material is used for this purpose, while the opposite process (alpha synchronization, i.e. an increase in spectral power) occurs when visual material is used (van Ede et al, 2017). Furthermore, the alpha range is not unique, it can be divided into a lower (8-10 Hz) and an upper alpha band (10-12 Hz), and these two ranges reflect different cognitive processes. Klimesch (1999) found that only the anticipation of the next trial led to a change in the representation of the alpha rhythm, which he attributed to the attention effect, but this effect was only reflected in the lower alpha band. The semantic processing of the data was reflected in the upper alpha region. In the aforementioned study, a specific methodology was used in which time series of data before and after the presentation of the stimuli were analyzed separately. What is even more interesting is that the changes in the lower and upper alpha regions showed the opposite trend. There was a synchronization of the waves in the lower alpha range and a desynchronization in the upper alpha range. Despite the fact that the *beta* rhythm has often been studied in the context of different types of tasks (motor, perceptual and cognitive tasks that test different processes (attention, working memory, long-term memory)), oscillations in this frequency range are among the least understood (Engel & Fries, 2010). This rhythm is traditionally associated with sensorimotor functions (Pfurtscheller & Lopez da Silva, 1999; Pfurtscheller at al., 1996), and it can be concluded that it is particularly pronounced during steady contractions and that its reduction occurs as a consequence of the preparation and execution of a movement (Engel & Fries, 2010). The phenomenon of a reduction in the amplitude and representation of beta waves as a result of the preparation and execution of voluntary movements over the sensorimotor areas has been known for a long time and is referred to as event-related desynchronization (ERD) (Pfurtscheller & Lopez da Silva, 1999). The opposite process occurs after the execution of a movement, when the beta wave representation increases compared to the baseline/control state, which is referred to as event-related synchronization (ERS) (Pfurtscheller & Lopez da Silva, 1999). Research shows that even just imagining performing a motor activity leads to the suppression of the beta rhythm (de Lange et al., 2008). Regarding the synchronization of the beta rhythm after the execution of movements, research has gone a step further than just confirming the existence of this phenomenon and it has been found that based on the degree of synchronization in the sensorimotor cortex, the speed of movement execution can be predicted, as a higher degree of synchronization is associated with the execution of slower movements (Zhang et al., 2020). In addition to the execution of the movements themselves, changes in the oscillations of the *beta rhythm can also be observed in the context of cognitive processing*, and in the meta-analysis mentioned above (Chikhi et al., 2022) it was found that the representation of this rhythm increases as a function of the increase in cognitive load.

In this study, a psychomotor task was used, namely three Fitts' tapping tasks. These are tasks whose difficulty is objectively expressed in the amount of information load, which is measured in bits. These tasks thus differ from all previously used tasks for monitoring changes in the dynamics of EEG activity due to complexity manipulations. The tasks are named after the researcher who designed them and refer to the successive alternative hitting of two targets of the same width (W) spaced at a certain distance (A-amplitude). Based on these two parameters, the difficulty of the task is determined using the formula ID (index of difficulty) = log2(2A/W) (Fitts & Peterson, 1964). By combining four different widths (0.5, 1, 2, 4 cm) and three different amplitudes (4, 8, 16), 12 combinations of tasks are possible, ranging in difficulty from 1 bit (the widest targets (4 cm) at the smallest distance (4 cm)) to 6 bits (the narrowest targets (0.5 cm) at the greatest distance (16 m)). With these tasks, it is possible to have more than two levels of difficulty, which is the most common case in the studies presented so far, which aimed to observe changes in the oscillations of EEG rhythms. It should be emphasized that every psychomotor task contains both, motor and cognitive component, the only question is in what proportion these two components are represented. In the Fitts' tapping tasks in particular, the cognitive component increases as the difficulty of the tasks increases and the motor component decreases as the number of hits decreases (Brečić & Manenica, 2008). With this in mind, the aim of this work was to determine how sensitive the changes in spectral power in different frequency ranges (alpha (8-12 Hz); beta (13-30 Hz) and theta (4-7Hz)) are to changes in the objective difficulty of Fitts' tapping tasks, expressed in bits. But before that, it should be determined whether the representation of the EEG waves changes during the performance of the task compared to the resting phase, especially compared to the task with the lowest level of difficulty (2 bits). The spectral density of the alpha, beta and theta rhythms is expected to be a parameter that is sensitive to load changes. Since the alpha rhythm is most pronounced during resting phases (in the parietal part of the cortex (Halgren et al., 2019)), this rhythm is expected to be the most sensitive to distinguish resting phases from phases of task performance. Even for the task with the lowest difficulty (2 bits). However, both beta and theta spectral power are expected to discriminate periods of rest and periods of task performance, but also periods of task performance with different difficulty (2, 4 and 6 bits). With increasing load, a desynchronization of the alpha rhythm (decrease in spectral power) and a synchronization of the beta and theta rhythms (increase in spectral power) is expected. Considering the previous literature and the positions of the electrodes used in this study, the most pronounced changes in the representation of alpha waves are expected in the parietal region, for theta in the frontal region, while for beta it is unreasonable to make predictions as previous results are rather inconsistent.

METHOD

Participants

35 right-handed participants without a neurological diagnosis took part in this study. Their ages ranged from 19 to 22 years, which means that the sample is homogeneous in terms of gender and hand dominance, as well as age, to control for factors that may influence the dynamics of neurological activity.

Instruments

The Annett Hand Preference Questionnaire (Annett, 2004) is a questionnaire consisting of 12 items describing some everyday activities for which the respondent indicates which hand he or she uses. In this study, 9 items were used, i.e. items that were assumed not to be performed by the participants or only very rarely (e.g. Which hand do you use at the top of a broom while sweeping?) were excluded. Only participants who stated that they performed all 9 activities with their right hand were included in the sample.

A *BE Light 36-channel EEG device* (EBNeuro, Florence, Italy) was used for the EEG recording. EEG activity was monitored with 13 active electrodes and a monopolar recording method was used with the reference electrodes placed on mastoids. All electrodes were made of silver chloride (Ag/AgCl). Four channels were used for electrooculographic monitoring, i.e. monitoring of vertical and horizontal movements, using a bipolar recording mode. All electrodes, active and reference electrodes, were integrated into the cap.

Brain Vision Analyzer v2.0 software (Brain Products GmbH, Gilching, Germany) was used to analyze the collected data. It allows a variety of data processing methods as well as the use of different algorithms for data preparation before final analysis. Among other things, the program enables the removal of artefacts from the EEG caused by eye movements, which are very pronounced when performing Fitts' tapping tasks.

A modified *electronic version of Fitts' tapping tasks* consisting of a base connected to a computer on which A4 format discs are placed with two targets of a certain width and a certain distance between them. Three tasks, i.e. three levels of difficulty, were used: 2, 4 and 6 bits. The 6-bit task is defined by 0.5 cm wide targets and amplitude of 16 cm. The 2- and 6-bit tasks can be defined with different combinations of target widths and their spacing or amplitudes. In this study, targets with a width of 4 cm and an amplitude of 8 cm were used for the 2-bit task and targets with a width of 2 cm and an amplitude of 16 cm were used for the 4-bit task. These tasks, i.e. combinations of width and amplitude, were chosen because a previous study (Brečić, 2007) found that these combinations deviated the least from the regression line between task difficulty and speed of task performance. The device enables the registration of inter-tap intervals.

Procedure

The data presented here were collected as part of a larger study that included EEG and cardiovascular activity recording during the performance of a series of psychomotor tasks (simple tapping task, Fitts' tapping task, assembly line work simulation, and the choice reaction time tasks). Due to the long duration of the measurement, participants came to the measurement three times at the same or approximately the same time of day to avoid circadian effect, since circadian modulation of brain electrical activity (Croce et al., 2018), but also body temperature and cardiovascular activities (Gregov, 2003) have been demonstrated. The subjects always performed the three Fitts' tapping tasks (2, 4 and 6 bits) in the same measurement, and each task was performed for 15 minutes. The order of performing the tasks was rotated according to the Latin square principle. The monitoring of EEG activity included 13 electrodes selected on the basis of previous studies in which these positions or regions were found to be essential for the execution of voluntary movements (Gerloff et al.; 1998, Singh & Knight, 1990). The electrodes were placed at the following positions: Fz, FCz, Cz (mesial frontocentral cortex, which includes the supplementary motor area), FC3, C3, CP3 (lateral premotor area, primary motor and primary somatosensory area - left hemisphere), FC4, C4, CP4 (lateral premotor area, primary motor and primary somatosensory area - right hemisphere), F3 and F4 (prefrontal cortex) and P3 and P4 (superior parietal cortex). Before starting the recording, the resistance of each electrode was checked, which should be less than 5 kΩ.

EEG was also recorded during the 5-minute rest period that preceded the performance of the tasks and during which the subjects sat with their eyes open. In this paper, the analysis made on the time series of the first 5 minutes of performing the tasks are presented. The introduction of an additional variable related to the duration of the task would exceed the appropriate level of complexity for one paper, considering that the results are related to different types of EEG waves, regions or electrode positions, and the difficulty of the tasks.

A Fourier transformation was performed for each data set, and spectral power (μV^2) in the alpha, beta, and theta bands was used as the dependent variable. Prior to performing the spectral analysis, data preparation was made, which included: data filtering (from 0.5 to 250 Hz, as the sampling frequency was 1000 Hz), removal of specific artefacts caused by eye movements (particularly pronounced in the frontal electrodes), and segmentation (splitting the time series into two-second segments due to data stationarity). Descriptive and inferential data analysis was done in Statistica 14 (TIBCO Software Inc., 2020).

RESULTS

First, the basic descriptive parameters of the analyzed variables are presented (Table 1). These variables represent the spectral power (μV^2) in different frequency bands (alpha, 8-12 Hz; beta, 13-30 Hz; theta, 4-7 Hz), different electrode positions and different experimental situations, i.e. at rest and when performing the Fitts' tapping tasks. In addition to *M* and *SD*, indexes of skewness (*IS*) and kurtosis (*IK*) were also calculated. For alpha activity, the *IS* ranged from 0.80 to 2.31 (*SE*=0.40) and the IK from 0.16 to 3.73 (*SE*=0.78), for beta activity the *IS* ranged from 0.61 to 2.16 and the IK from -0.43 to 5.41, while for theta activity the IS ranged from 0.33 to 2.94 and the IK from -0.70 to 5.13. It can be seen from the parameters mentioned that the distributions of the results deviate from the normal distribution, but these deviations are not so extreme that parametric analyses would necessarily have to be rejected (Kline, 2016). It should also be considered that the statistical power of non-parametric tests is lower and, in this case, they are not even suitable for answering the questions posed.

The next step of the analysis was to examine the differences in the power of the spectrum in different frequency bands (alpha, beta and theta) at rest compared to performing three Fitts' tapping tasks. For this purpose, a two-way repeated measure analysis of variances (ANOVAs) was performed. Since the rule of sphericity was violated, the Greenhouse-Geiser correction was conducted and adjusted p values were marked. These results are shown in Table 2. The interaction effect of the situation (resting vs. performing the task) and the position of the electrodes is not specified, as its interpretation is too complex and is not relevant for this paper.

In all three frequency ranges a difference in the power of the spectrum was found when periods of rest were compared with periods of task performance, regardless of the task difficulty. Regarding the effect size within beta and theta rhythm related to the experimental situations (resting and performing the task), we see that the effect sizes are large, as the partial eta squared values range from 0.27 to 0.60. The values for the alpha rhythm are somewhat

Table 1 The basic descriptive parameters of the examined variables- spectral power (μV²) in the alpha, beta and theta rhythm during rest and when performing Fitts' tapping tasks

Frequency band	El. pos.	Resting state		2 bits tapping task		4 bits tapping task		6 bits tapping task	
		M	SD	M	SD	M	SD	M	SD
Alpha	F3	24.05	16.66	24.20	13.29	23.22	12.34	24.39	11.99
	F4	25.58	18.76	24.14	13.39	23.58	13.05	24.18	12.89
	FC3	24.71	17.80	22.50	12.26	21.80	11.08	23.07	11.17
	FC4	27.86	20.96	23.92	13.15	23.59	13.11	23.71	12.65
	C3	33.08	24.93	23.47	13.76	23.03	12.57	24.20	12.26
	C4	33.33	25.67	24.87	13.68	25.23	14.51	24.90	13.36
	CP3	40.87	36.73	26.45	16.64	25.80	16.04	27.12	14.77
	CP4	41.97	38.91	27.39	15.20	28.03	16.37	27.81	15.07
	P3	52.86	41.01	31.61	20.69	31.54	21.08	32.35	18.75
	P4	52.09	37.42	32.53	17.83	34.60	18.88	35.69	19.81
	Fz	30.12	21.21	29.64	15.35	28.51	14.47	28.93	14.14
	FC	33.29	24.16	32.12	15.60	31.66	14.85	31.17	14.60
	Cz	37.33	16.66	31.49	15.98	31.86	15.77	31.04	14.45
Beta	F3	26.42	9.68	32.26	18.38	33.27	15.07	41.31	20.12
	F4	24.96	9.92	30.61	16.16	32.66	13.80	39.92	18.12
	FC3	24.66	11.09	31.55	18.80	32.77	15.08	40.62	20.21
	FC4	23.95	9.38	29.78	15.15	32.16	13.83	38.94	16.71
	C3	22.90	9.23	33.10	20.09	35.03	16.66	43.47	20.87
	C4	23.49	9.30	30.84	16.32	33.83	15.81	39.85	16.89
	CP3	22.28	9.63	38.29	24.07	41.26	21.46	50.39	23.58
	CP4	22.61	9.57	35.71	20.45	40.40	21.01	45.45	20.28
	P3	24.24	12.15	48.93	31.59	53.37	29.35	63.13	29.27
	P4	25.21	12.40	49.94	31.85	54.64	35.48	66.32	34.47
	Fz	23.89	9.25	32.20	17.79	33.72	14.98	41.56	19.57
	FC	25.37	10.33	33.92	17.58	36.09	15.61	43.31	19.59
	Cz	25.00	10.87	34.74	18.19	37.06	15.87	43.62	19.61
Theta	F3	19.79	8.87	26.39	8.79	24.46	8.09	23.73	7.07
	F4	20.69	9.57	25.75	9.25	24.35	8.80	23.85	8.36
	FC3	17.79	7.62	22.83	7.13	22.07	5.81	22.20	6.38
	FC4	20.29	8.76	23.61	7.22	23.24	7.67	23.00	7.25
	C3	16.30	6.49	20.68	6.26	21.78	5.70	20.71	6.04
	C4	18.34	7.53	21.32	6.28	21.91	6.28	21.68	6.92
	CP3	15.47	6.05	20.12	7.24	22.55	6.96	20.36	6.46
	CP4	16.92	6.47	20.13	6.10	22.90	6.63	21.01	6.78
	P3	15.42	6.33	21.14	8.26	29.76	17.89	21.40	7.23
	P4	16.37	6.48	21.94	7.74	25.67	8.33	22.37	8.21
	Fz	27.53	12.25	36.69	12.60	34.29	11.82	33.00	10.04
	FC	29.63	11.55	39.52	11.79	37.67	10.40	37.36	10.56
	Cz	25.18	9.31	32.29	9.19	33.15	8.69	32.42	9.52

Table 2 Results of repeated measures ANOVAs - changes in spectral power (μV^2) of alpha, beta and theta rhythms at rest compared to the periods of the Fitts' tapping tasks performance; N=35

Frequency band	Source of variation	*df*	*F*	η_p^2
alpha	Resting vs 2 bits	1/34	5.42*	.14
	Electrodes	12/408	15.68**	.32
	Resting vs 4 bits	1/34	5.16*	.13
	Electrodes	12/408	17.09**	.34
	Resting vs 6 bits	1/34	5.42*	.14
	Electrodes	12/408	16.63**	.34
beta	Resting vs 2 bits	1/34	12.74**	.27
	Electrodes	12/408	16.26**	.32
	Resting vs 4 bits	1/34	30.39**	.47
	Electrodes	12/408	20.83**	.38
	Resting vs 6 bits	1/34	50.23**	.60
	Electrodes	12/408	23.72**	.40
theta	Resting vs 2 bits	1/34	28.20**	.45
	Electrodes	12/408	90.07**	.73
	Resting vs 4 bits	1/34	33.99**	.51
	Electrodes	12/408	33.16**	.63
	Resting vs 6 bits	1/34	30.68**	.48
	Electrodes	12/408	94.32**	.74

Significance levels marked adjusted $p < 0.05$* and $p < 0.01$**.

lower and we can speak of medium effect sizes. The power of the spectrum of the alpha rhythm is greater during periods of rest than during periods of task performance, while the direction of change is opposite for the beta and theta rhythm. As far as the alpha rhythm is concerned, a difference in the strength of this spectral range was found depending on the position of the electrodes. For all three Fitts' tapping tasks, differences in spectral power are a consequence of the differences detected at positions P3 and P4, as determined by the Scheffe test with a significance level of $p<.01$. Beta power was found to be higher during performance 6-bit task than during rest in all positions. When comparison was made for resting and 4-bit and 6-bit task performance, there was no difference for F3, F4, FC3 and FC4 positions. For other positions Scheffe test showed that the differences were significant at a level of $p<.001$. For the theta rhythm, it was also found that the power of the spectrum was higher in all positions ($p<.001$) during the performance of the 2-bit and 6-bit tasks compared to the resting phase. Differences ($p<.01$) were found in the following positions when comparing the rest phase and the performance of 4-bit task: C3, C4, CP3, CP4, P3, P4, Fz, FC, Cz.

The following results relate to the changes in the spectral power of alpha, beta and theta rhythm while performing Fitts' tapping tasks (2, 4 and 6 bits).

Table 3 Results of repeated measures ANOVAs - changes in spectral power (μV²) of alpha, beta and theta rhythm during the performance of three Fitts' tapping tasks (2, 4 and 6 bits; N=35

Frequency band	Source of variation	*df*	*F*	η_p^2
alpha	Task difficulty (bits)	2/68	0.06	.01
	electrodes	12/408	28.01*	.45
beta	Task difficulty (bits)	2/68	6.80**	.17
	electrodes	12/408	35.05**	.51
theta	Task difficulty (bits)	2/68	1.44	.04
	electrodes	12/408	65.44**	.71

Significance levels marked $p < 0.05$* and $p < 0.01$**.

A repeated measures ANOVA was also carried out for this purpose. The results are shown in Table 3. As before, no interaction effects are shown in this case either.

The results show that the task difficulty influenced the changes in the beta power, and a comparison of these data with the descriptive statistics shows that the power increased with increasing task difficulty. The post-hoc analysis (Scheffe test) showed that the spectral power differed when comparing periods of performing tasks of 2 and 6 bits as well as for 4 and 6 bits, while there was no difference when comparing 2 and 4 bits. To answer the question in which areas this change was found, further processing was performed, i.e. a one-way ANOVA for repeated measures for each electrode. These results are shown in Table 4,

Table 4 Results of repeated measures ANOVA - changes in the beta power (μV²) on each electrode during the performance of Fitts' tapping tasks (2, 4 and 6 bits); N=35, df=2/68

Electrode pos.	*F*	η_p^2	Post-hoc (Scheffe)	
			2 vs 6	4 vs 6
F3	5.78**	.15	p=.011	p=.027
F4	7.63**	.18	p=.002	p=.019
FC3	5.27**	.13	p=.015	p=.041
FC4	8.33**	.20	p=.001	p=.018
C3	5.85**	.15	p=.008	p=.038
C4	7.77**	.19	p=.001	p=.041
CP3	6.07**	.15	p=.005	p=.047
CP4	6.66**	.16	p=.002	p=.017
P3	5.18**	.13	p=.006	p=.104
P4	7.27**	.18	p=.001	p=.308
Fz	6.68**	.16	p=.005	p=.021
FC	6.49**	.16	p=.004	p=.036
Cz	5.50**	.14	p=.008	p=.068

Significance levels marked $p < 0.01$**.

with the associated post-hoc tests. Although the theoretical post-hoc comparisons include three possible relations (2 bits vs. 4 bits; 2 bits vs. 6 bits and 4 bits vs. 6 bits), the comparison 2 bits vs. 4 bits was not included in the post-hoc analysis, considering the aforementioned results that show no difference in beta power for these two conditions.

The results show that the difference in beta power was found for all electrode positions. Furthermore, a difference in spectral power was found for all positions when comparing 2- and 6-bit tasks and when comparing 4- and 6-bit tasks there was no difference in parietal region (P3 and P4). Higher task difficulty is associated with higher beta power.

DISCUSSION

The load caused by the fulfilment of tasks is one of the key concepts in psychological research. This is related to the fact that people are often exposed to high demands on our cognitive and physical resources, which leads to overload situations. Such overload can have negative health consequences or lead to errors or accidents (Zoer et al., 2011). From a research perspective, cognitive load can be assessed in different ways: by subjective assessments, by task performance parameters (e.g. reaction time) or using psychophysiology (e.g. EEG or ECG). Each of these methods has its advantages and disadvantages, but for each of them the "starting" point" is important, which refers to the fact that it is difficult to quantify the input, i.e. the difficulty of the task itself. Therefore, one of the main motivations for conducting this research was the use of Fitts' Tapping Tasks, the difficulty of which is expressed precisely in bits. That distinguishes this study from other studies that have investigated the dynamics of the nervous system due to changes in task complexity. In addition, most previous studies have used only two levels of complexity (an easier and a more difficult task), which is another unique feature given that three levels were used in this study.

The spectral powers in the alpha, beta and theta frequency bands were chosen as dependent variables primarily because they were most frequently used in previous studies of cognitive (over)load and in studies in which psychomotor tasks (primarily beta) were used. Regarding the changes in the power of the spectrum in the frequency bands mentioned, it can be said that significant differences were found for all of them between the rest phase and the phases in which tasks were performed. These data were expected, considering that the cognitive processes change significantly between these two situations, even when it comes to the difficulty level of the task of 2 bits, regardless of the fact that this task is usually categorized by the respondents as an extremely easy task (e.g. Brečić, 2007). In the alpha rhythm, desynchronization occurs during task performance, which was expected if one considers that the alpha rhythm dominates in the EEG during the quiet waking state (Halgren et al., 2019). The alpha rhythm does not seem to be the most discriminative when it comes to periods of rest phases and phases of task fulfilment, as expected. This can be concluded from the fact that the effect sizes for the beta and theta rhythms are larger than for the alpha rhythm. The explanation for this result lies in the fact that the rest phase is always somewhat "controversial". The reason for this is that, regardless of the instruction to the subjects to relax during the resting phase, we can never be sure that the participants will actually do so, i.e. we cannot control their thoughts. If they are concentrating on something that is stressing them out, then the rest period is not a "real" rest period. The positions where the differences were found relate to the parietal area, which is consistent with previous findings that alpha is most pronounced in the parietal region (e.g. Halgren et al., 2019).

Higher spectral power was obtained in the beta and theta frequency bands during performance of tasks of all difficulty levels compared to rest. These changes are not localized as in the alpha rhythm, but dispersed, and the direction of the changes is such that the synchronization of these waves indicates greater cognitive load.

As for the changes in spectral power caused by the task difficulty manipulation, it was found that these changes were only significant for the beta rhythm, but not for the alpha and theta frequency bands. There are several possible reasons why alpha and theta rhythms were found to be non-discriminatory. Theta rhythm has been shown to be a good indicator of cognitive load in previous studies, but only for certain types of tasks. These are mostly tasks that test working memory (e.g. Klimesch, 1999) and this cognitive process is not present when performing Fitts' tapping tasks. For the alpha rhythm, it was found that one cannot speak of a single rhythm, but that it is divided into two sub-rhythms that may respond differently due to the increased conjunctive load. In this study, the alpha range was not subdivided but observed as a single frequency band. It is a paradigm that is also very commonly used in other studies, but this does not mean that it has no shortcomings. Another problem with alpha and theta rhythms is that they cover a small frequency range (4-7 Hz, theta; 8-12 Hz, alpha), in contrast to the beta rhythm, where the frequency range is much larger (13-30 Hz). The use of a predefined frequency range may result in alpha and beta rhythms not being adequately captured, even in people of the same age, as there are large inter-individual differences in the frequencies at which these rhythms occur. The way the subjects performed the Fitts' tapping tasks meant that after each hit on the target, preparation for the execution of the next movement began automatically, so that it was not even possible to record the period "after the execution of the movement" in which the subjects did nothing. Thus, if the change in the spectral power reflected movement execution, we would expect a suppression of the beta rhythm, and the opposite was achieved, which is consistent with previous findings of an increased spectral power due to an increase in cognitive load. Based on this study, it can be said that the relationship between the level of difficulty and beta power is a growing function that is not linear, as there is no difference in spectral power for 2 and 4 bits, but there is for 4 and 6 and 2 and 6 bits. An additional argument in favor of attributing the changes in the spectral power to the cognitive component is the fact that there was no difference in comparisons of 2 and 4 bits, but there was a difference in comparisons of 2 and 6 or 4 and 6 bits. This trend of change is parallel with changes observed in the intertap intervals. As the difficulty of the task increases, the intertap interval, expressed in milliseconds, increases significantly ($F(2,78)=953.18$; $p<.001$; $M_2=268.52$; $M_4=414.82$; $M_6=742.79$), but the difference in the increase in the intertap interval is smaller (t $(34)=11.79$, $p<.001$) when comparing tasks with 2 and 4 bits (146.3 ms) than when comparing tasks with 4 and 6 bits (327.97), although in both cases it is an increase of 2 bits. To confirm such a conclusion, it would be better to have subjective assessments of the difficulty of the tasks. In this case, it would be possible to compare three different parameters indicating the difficulty of the task: psychophysiological measurements (spectral power of EEG waves), intertap intervals and subjective assessment. Unfortunately, a comparison with the subjective assessment is not possible, as that data was not collected as part of this study.

The changes in the beta power are not localized but diffuse and include almost all electrode positions when comparing the periods during the 2- and 6-bit tasks performance and almost all electrode positions when performing 4- and 6-bit tasks. The results of this work did not help to capture some specific areas. One of the reasons for this could be that a period of 5 minutes is a very long period in the context of EEG analyses. It is possible that a shorter period of time to perform the tasks would allow for more accurate localization.

Finally, it is necessary to point out some advantages and disadvantages of the conducted study. The relatively large number of participants can be emphasized as an advantage. In studies of this type, it is not unusual for the number of participants to be around 10, so that the statistical power is often impaired. In addition, this is one of the few studies that have more than two levels of complexity, and these levels are objectively determined. One shortcoming is that despite the fact that beta rhythm has been established as a good indicator of cognitive load, we still do not know which cognitive process is involved. It is possible that these processes refer to vigilance, alertness, attention or something else. It would also be useful to collect data related to the subjective assessment of the difficulty of tasks. In clarifying the question of what processes the changes in beta rhythm are attributable to, it would also be good to have a task where it is possible to analyze the data related to the preparation of the movement itself and the execution of the movement separately. This would mean that the method of event-related potentials would be applied. It would be particularly interesting to observe this in connection with the objective increase in task difficulty. In future studies, it would also be useful to use more tasks with different levels of difficulty in order to obtain a more precise relationship between level of difficulty and beta power.

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Osjetljivost EEG valova na promjene u kompleksnosti psihomotornih zadataka

Sažetak: Prijašnja istraživanja upućuju na to da promjene u snazi spektra alfa, beta i theta ritma mogu biti dobri indikatori opterećenja nastalog kao posljedica izvođenja različitih kognitivnih i psihomotornih zadataka. U ovom istraživanju, neuralna aktivnost bilježena je za vrijeme izvođenja psihomotornih zadataka Fittsova *tappinga*. Izabrani su ovi zadaci s obzirom na to da je njihova težina objektivno kvantificirana i izražena u bitima. Korišteni su zadaci čije je opterećenje iznosilo 2, 4 i 6 bita. Cilj ovog istraživanja bio je utvrditi koliko su promjene u snazi spektra triju EEG frekvencijskih područja osjetljive na promjene u težini zadataka. Sudjelovalo je 35 sudionica, dešnjakinja, bez neuroloških dijagnoza, čija se dob kretala u rasponu od 19 do 22 godine. Tijekom izvođenja zadataka sniman je EEG i elektrookulografija (EOG). EEG je sniman i u razdoblju mirovanja tijekom kojeg su sudionice sjedile sa zatvorenim očima. Korištene su sljedeće pozicije elektroda: F3, F4, FC3, FC4, C3, C4, CP3, CP4, P3, P4, Fz, FC, Cz. Rezultati potvrđuju da postoji razlika u snazi spektra za sva tri frekvencijska područja (α, β and θ) ako se uspoređuje razdoblje mirovanja s razdobljima izvođenja zadataka. Promjene u snazi alfa ritma pronađene su u parijetalnom području (supresija alfe za vrijeme obavljanja zadatka), dok su promjene u beta i theta ritmu disperzirane te ih karakterizira veća spektralna snaga za vrijeme obavljanja zadataka. Promjene u težini zadataka rezultirale su promjenama u snazi beta ritma, ali ne i alfa i theta ritma. S porastom težine zadataka raste snaga beta ritma na svim korištenim pozicijama, ali ove promjene nisu linearne s obzirom na to da razlike postoje kada se usporedbe rade za zadatke od 2 i 6 bita, 4 i 6 bita, ali ne i za 2 i 4 bita. Ove su promjene interpretirane kao posljedica promjena u kognitivnom opterećenju.

Ključne riječi: alfa, beta, theta, zadaci Fittsova *tappinga*

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