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How EEG activity changes during tasks requiring sustained attention?

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Abstract: Several studies have investigated neurophysiological variables indicating the quality of reading and have found a relationship between performance on reading tests and frontal EEG theta and beta powers, as well as the degree of correlation between frontal and posterior EEG activities. Frontal beta activity indicates alertness and the development of effective cognitive control, while an increase in theta activity implies the use of working memory. A strong correlation between frontal and posterior areas indicates efficient communication between secondary visual areas that aid reading and frontal areas responsible for maintaining attention.

In this study, we investigated changes in EEG activity that may be related to reading quality and recall of the read text. We recorded the EEG activity of 20 high school students (aged 16-19) using the Emotiv Epoc+ device. The reading tasks were history lessons, appearing on a laptop screen. The first lesson was preceded by relaxation, while the second by a series of mathematical tasks. Following each reading, participants completed a task sheet related to the text. At the end of the task series, students rated the difficulty of the tasks, and their performance, anxiety and fatigue. After removing artifacts, the EEG recordings were divided into frequency bands. We determined the power of each frequency band and the correlation between the frontal and posterior electrodes on both sides in the theta and beta bands.

For the first history text, students' performance and perceived task difficulty showed a negative correlation, while for the second text, no such correlation was found. None of the EEG characteristics correlated with students' self-reported fatigue. Beta activity was higher during the second reading tasks and showed no correlation with the task difficulty or performance. During the first reading the correlation of the theta activities between the frontal and posterior areas was higher than during the second reading task on both side, while on the right side in addition to this we found higher level correlation in the beta band as well. The decreased level of correlation between frontal and posterior areas indicated the weakening of the communication between them and negatively correlated with the score of the math tasks.

Our measurements revealed differences in EEG activity during the two reading tasks, indicating that with fatigue working memory use and, especially on the right side,

communication between frontal and posterior areas became less effective. Beta and theta band powers and the level of correlation between frontal and posterior areas therefore promising parameters to be used for monitoring attention during reading.

Keywords: EEG, beta activity, reading comprehension, theta activity

1 Introduction

Electroencephalography (EEG) has emerged as a valuable technology for decoding different cognitive processes, like language processing, reading. Brain dynamics involved in reading comprehension have been extensively studied lately and different spectral domains of the EEG were attributed to reading quality. In traditional educational systems reading skills are accessed through comprehension questions. These take time to prepare and answer, moreover they disrupt the reading process. EEG recording offers an alternative, unobtrusive method to record brain activity during reading and correlate changes in them with reading quality (Yuan et al., 2014).

1.1 Reading comprehension

Reading is a cognitively demanding ability requiring synchronization between several neural networks supporting visual, language processing and higher-order abilities. Nowadays literacy is an essential higher order skill required for navigating complex information environment. It is a skillset that enables us to evaluate, interpret and respond to different media messages or to make good academic progress. The ability to read proficiently enables individuals to collect, interpret and synthesize information and helps develop critical thinking (Alvarez-Alonso et al., 2025).

Reading comprehension involves a complex interplay of cognitive processes like word recognition, language comprehension and semantic integration (Su et al., 2003). It is a two-way process that integrates information from the text with information from prior knowledge. Differences in reading comprehension are not indicative of a lack of intelligence, they rather reflect specific neurocognitive differencess (Morais & Kolinsky, 2020). A core component of reading is phonological awareness, the ability to solve tasks that require the analysis and synthesis of sounds within syllables; in developmental dyslexia, this process has certain deficits (Wagner et al., 1997).

Studying the brain activity underlying reading proficiency might provide insight into the neural mechanisms of reading difficulties and also helps develop a method to measure reading proficiency reliably and objectively. This measurement option can be useful, among other things, when testing distance learning materials or advanced courses using specialized language.

1.2 EEG bands correlating with reading comprehension

Neuronal activity is reflected by a broad range of rhytms, which are associated with different physiological activities and cognitive functions (Buzsáki, 2006). Activities within distinct oscillations help forming neuronal assemblies which underlie the different aspects of lingistic processing (Weiss & Mueller, 2012). Usually, the brain oscillations are subdivided into five main frequency bands: delta (0.5–3.5 Hz), theta (4–7,5 Hz), alpha (8–13 Hz), beta (13,5–30 Hz), and gamma (>30 Hz) (Buzsáki, 2006). Cognitive processes related to reading associated with theta, beta, and gamma activities. Since measuring gamma activity is difficult with portable EEG devices that are easy to use in educational settings, we focused on examining theta and beta activities.

Theta activity is associated with the use of working memory and reflects short term memory processes (Klimesch, 1999). Frontal theta activity increases during mental calculations or sentence processing (Röhm et al., 2001). It is higher when the task is more demanding for example during oral reading or when the text is difficult. Dislexic children also show higher theta activity than neurotypical children during reading (Galin et al., 1992). Network efficiency in theta band is higher for good readers, it is shown by the higher functional connectivity strength and correlation coefficient values between frontal and posterior reading related areas (Fraga-González et al., 2021).

Beta activity is linked to alertness and has a role in motor and language processing. Beta synchronization has been correlated with word encoding and syntactic unification in determining sentence meaning (Weis & Mueller, 2012). In skilled readers beta power is enhanced during reading, and may reflect efficient neural mechanisms for text comprehension and linguistic processing (Álvarez-Alonso et al., 2025). Frontal beta oscillations are also associated with top-down control mechanisms, and reflect the levels of cognitive control in order to properly adapt to task demands (Stoll et al., 2015). Computer simulations predict that betal rhythms facilitate the formation of short-term memory (Kopell et al., 2011). Therefore, the level of frontal beta activity correlates with attention, active thinking and associated with good performance in reading tasks (Zaeni et al. 2019). Network connectivity, the coactivation and correlation of beta oscillations between regions reflect efficient neuronal communication. During reading a strong correlation between frontal and posterior areas indicates efficient communication between posterior secondary visual areas, areas connected to language processing and frontal areas responsible for maintaining attention (Álvarez-Alonso et al., 2025). This synchronouos (correlated) activity was observed in experienced readers during reading.

2 Materials and Methods

2.1 Participants

In this study, we recorded the EEG activity of 20 high school students (aged 16-19) using the Emotiv Epoc+ device. Students had no learning disabilities, and showed good or outstanding acedemic results. The differences in their reading or mathematical skills reflected the variance found in normal population. The reading tasks were history lessons adapted from the public portal of the National Institute for Public Education (https://www.nkp.hu). The study design was approved by the Eszterházy Károly Catholic University Ethics Committee, and the study was conducted according to the criteria set by the declaration of Helsinki (https://www.wma.net/policies-post/wma-declaration-of-helsinki/). Both the students and their parents received a document about the experimental procedure, the safety of EEG measurements and data handling. After reading that, they agreed to participate in the study by signing a consent. The experimental setup was similar to our previous studies (Antal et al., 2017; Emri and Antal, 2022). The tasks and instructions appeared on a laptop screen, alternating between relaxation, math and history tasks. There was no time limit on the tasks, everyone could work at their own pace. The first history lesson was preceded by relaxation, while the second by a series of mathematical exercises. After reading a history lesson, participants completed a work-sheet related to the text. At the end of the task series, students rated the difficulty of the tasks, and their performance, anxiety and fatigue levels.

2.2 EEG data processing

EEG recordings were offline analyzed in Python (Python software foundation, 3.8.10), using the 'scipy' (1.8.0) package (Jones et al., 2001). Raw data was band-pass filtered with 0.5 Hz and 30 Hz cutoff frequencies, then standardized to zero mean and unit standard deviation. To limit the effect of high peaks, we clamped the data to the [-6, +6] range. For spectral analysis we used a Tukey window of 2 seconds with a shape parameter of 0.25, 1 second overlap between segments, and segmentwise linear detrending. After removing artifacts, the EEG recordings were divided into frequency bands. We determined the power of each frequency band. We also determined the correlation between the frontal and posterior electrodes on both sides in the theta and beta bands. Relative EEG power values were calculated as the ratio of powers in a specific EEG band and the 1-25Hz frequency range. Data are presented as the average ± standard error. For comparisons between test scores or between the difficulty rates of the tasks Wilcoxon test (Bauer, 1972) was used. For comparing EEG band powers between the two reading sections the paired samples Student's T test. Correlations between the EEG data, tests and questionnaire values were appraised using Spearman's correlation coefficients (Gerőcs & Vancsó, 2023) was used.

3 Results

Neither the reading times of the two history lessons, nor the time used to solve the corresponding work-sheets differed between the two tasks. According to their rating by the students, the second lesson was easier than the first ($p=0,0088$), and accordingly their test scores were higher ($p=0.0015$). In the first test the result score was 5,76±3,24 while in the second 8,79±2,91.

Ranking the students according to their scores on the two history tasks yielded the same order, those who achieved an above-average score in the first task also performed outstandingly in the second. Based on their results, the students were similarly successful in both history tasks, both tasks required the same cognitive capacities.

3.1 Changes in EEG band powers established to monitor reading quality

The students read the first history lesson after 3 minutes of relaxation, while the second history lesson after they had to solve three math problems by mental calculation. They were only allowed to write down the final results. Students rated the math task as difficult as the first history lesson, and their scores were also similar (p=0,40). Since mental calculations are cognitively highly demanding tasks, we proposed that students would have difficulty to concentrate during the second reading task, while they could easily solve the first reading task. To achieve good scores in the second reading task they might need to activate mechanisms helping them maintaining sustained attention. Therefore, the differences between the EEG activities measured during the two reading tasks may most likely indicate greater mental effort and/or fatigue.

Theta and beta EEG band powers showed regional differences between the two readings. The average theta and beta activities were higher during the second reading than during the first. Among the electrode positions, the occipital region showed higher beta activity during the second lesson (Figure 1A). In the theta band, the correlation between frontal and posterior areas decreased on both sides by the second history reading task, and in the right side also in the beta band (Figure 1B). These results suggest less efficient information integration during the second reading. Lower correlation values between frontal and posterior areas are the signs of less efficient communication between these regions. Increased beta and theta power may be the result of a compensatory mechanism, increased use of short-term memory and higher levels of alertness might compensate for the reduced connectivity between the frontal and posterior areas.

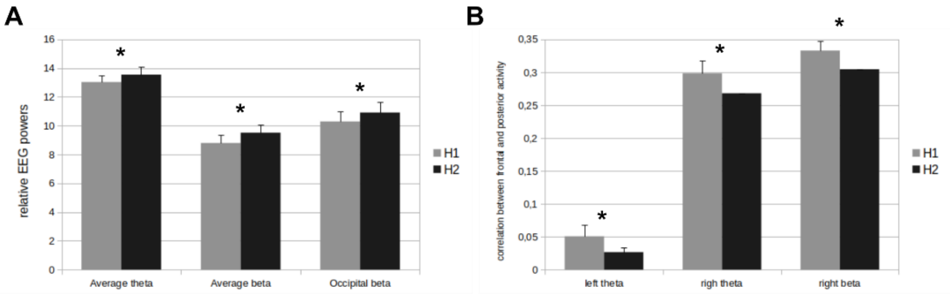

***Figure 1**. EEG band powers during reading. H1: first history lesson, H2: second history lesson. * p<0,05.*

3.2 Correlation analyses

We calculated Spearman correlation values between EEG parameters, test scores and self-reported tiredness, anxiety and difficulties of the tasks. None of the EEG parameters showed significant correlation with self-reported anxiety or fatigue. History and math test scores highly correlated, and self-reported difficulty rates of the first history and the math tasks showed negative correlation with the corresponding scores (Figure 2). The beta and theta EEG band powers during the second reading task, as well as the synchrony in the beta and theta bands, were correlated with test scores or self-reported difficulties. A high positive correlation was observed between EEG band powers and beta-band correlations of the first and second reading tasks. Theta band correlations did not show such a pattern. The preservation of high beta band correlation between left frontal and posterior areas correlated with the math score, those who could solve the math tasks showed high correlation values during the second reading task.

Self-reported difficulty of the first history lesson was negatively correlated with the frontal theta power, and with the beta band correlation values, while the results of all tests positively correlated with the beta band correlation values (Figure 3). This negative correlation suggests that students who found the first history lesson difficult had a less efficient use of their short-term memory, and the communication between their frontal and posterior brain areas was reduced (Figure 3).

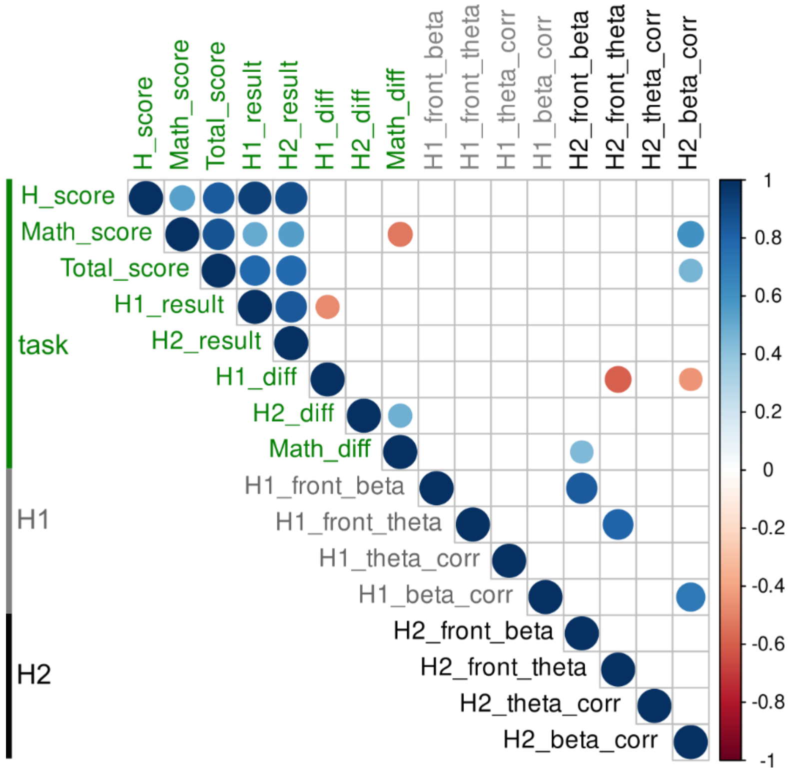

Figure 2. *Spearmann correlation values between EEG parameters, test scores, self-reported test difficulties. H: history task, Total score: the results of the math and history tasks together. Front: frontal, Theta corr: theta band correlation valus; beta corr: beta band correlation values. Blue: positive correlation, red: negative correlation. P<0,05.*

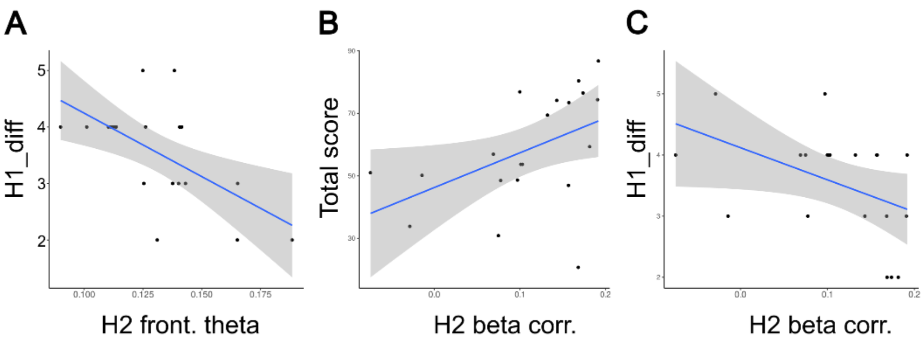

Figure 3. *H1 task difficulty (H1_diff) negatively correlated with the frontal theta activity (H2 front. theta), as well as with the correlation of frontal and posterior activity within the beta band (H2 beta corr.) during H2 task, while the result of all tasks (Total score) positively correlated with H2 beta correlation.*

4 Discussion

Previous studies revealed complex relationships between different neurophysiological measurements and reading comprehension (Álvarez-Alonso et al., 2025; Fraga-González et al., 2021; Röhm et al., 2001). These studies compared dyslexiv and neurotypical children or proficient and struggling readers, and found that theta and beta band powers as well as the correlation of the activities of frontal executive and posteriol visual or language-related areas show characteristic differences between the two groups. Good reading quality was assocoated with elevated beta and theta activities and beta band synchronization between frontal and posterior areas highlighting the importance of these networks in efficient cognitive processing of language-related information (Shurz et al., 2015).

We tested these EEG parameters in a normal population to find a correlation with good text recall or mental fatigue. The participants in our measurements had no reading problems, and their school performance was good or outstanding, therefore the changes observed in the EEG reflect mechanisms activated by either high task demand or fatigue. The two tasks we compared were history lessons, the first reading task was after a relaxation period, while the second followed mathematical tasks. Since solving mathematical problems or doing mental calculations are demanding cognitive tasks (Hsu & Yao, 2023), we can assume that students had more difficulties to remain focused during the second lesson than the first. The changes we have detected are changes in brain activity due to increasing cognitive demand (Weiss & Mueller, 2012) and may also be early signs of deteriorating reading quality due to fatigue.

The importance of beta oscillations in language processing and cognitive control has been emphasized by Weiss and Mueller (2012) previously. They showed that the beta band power is higher in skilled than struggling readers. The increase of beta power reflects neuronal mechanisms enabling efficient linguistic processing. In our measurement students probably needed extra effort to solve the second task, since the mental calculation task was tiring, they needed a boost in their alertness level and reading related brain activities. Hence, their increased beta power ensures this efficiency crucial for reading comprehension and fluency (Mueller & Weiss, 2012).

The increase in theta band power reflects the intensive use of working memory (Gevins et al.. 1997). Different linguistic processes have no direct influence on theta oscillations (Röhm et al., 2001), therefore the increased theta band power reflects general processing demands, the more extensive use of working memory during the second reading session than during the first. Increased frontal theta power had been associated with task difficulty and also with practice, and it was suggested that it reflects the effort that focusing attention requires. Increased frontal theta power has been linked to both task difficulty and practice, and it has been suggested that theta band power reflects the effort required to focus attention (Gevins et al., 1997). Thus, the increase in the theta activity during the second reading session probably shows the increased effort students required to remain focused.

While high beta and theta band powers are associated with good quality reading the decrease in the correlation of frontal and posterior brain areas is a sign of declining reading quality (Schurz et al., 2015). High levels of correlation are a sign of increased synchronization within fronto-central-parietal networks helping the interaction of the different areas, When the synchrony in this network decreases the communication between frontal and posterior language-related areas became less effective. This can lead to poor reading fluency and comprehension in the long term. Increased beta and theta powers might partially compensate for the weaker interplay within the reading network but continuing to complete the task can lead to poor results, reduced learning efficiency, and even loss of motivation. Therefore, the changes in these EEG parameters can predict attention lapses and performance decline.

This prediction can be extremely useful when we need to monitor attention level in distance or hybrid learning environments. After the COVID-19 outbreak distance and hybrid learning methods exploded in schools. The role of technology in education was reimagined, new-technology-assisted learning tools, such as mobile devices, laptops, virtual laboratories appeared in schools and altered education methods. They have proven to be cost-effective and have also offered a solution to expanding access to education for individuals from remote, disadvantaged regions (Haleem et al., 2022). These digital tools make learning more appealing to children, however in this new online environment the evaluation of students' attention and engagement levels can be challenging. Especially hybrid classrooms require special methods for the measurement of effectiveness, since hybrid learning integrates both online and offline teaching, requiring an evaluation method that can be used in both environments (Zhuang et al., 2022). EEG recording can be such a method, it can be used in classrooms and in an online learning environment as well. There are promising results where there was a good correlation between the students' feedback and their attention level calculated from EEG data (Aggarwail et al., 2021).

5 Conclusion

EEG parameters, which have contributed to our understanding of the neural basis of reading comprehension and distinguish between proficient and struggling readers, appear promising for monitoring reading quality during tasks requiring prolonged, sustained attention. We propose that some of these EEG parameters may be suitable for detecting signs of increased mental effort or fatigue in students with normal reading ability.

The parameters that previous studies (Álarez-Alnso et al., 2021, Fraga-González et al., 2021, Yuan et al., 2014) associated with good reading quality in our measurement also showed positive correlation with the test scores, while self-reported difficulty values showed negative correlation with them. Also, the correlation of frontal and posterior areas decreased during the second reading task, indicating impaired communication between frontal executing and posterior language and visual information processing areas. We hypothesize that changes in beta and theta band power indicate the activation of a compensatory mechanism, leading to increased alertness and enhanced use of working memory, helping students to maintain attention and achieve good results on the second history task.

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