Chapter #16

THE CONTRIBUTION OF EEG RHYTHMS' CHANGES TO THE AUDIOVISUAL RECOGNITION OF WORDS IN UNIVERSITY STUDENTS WITH DYSLEXIA

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ABSTRACT
Dyslexia is one of the most frequent specific learning disorders often associated with phonological awareness deficits mainly concerning auditory and visual inabilities to recognize and discriminate phonemes and graphemes within words. Neuroimaging techniques have been widely used to assess hemispheric differences in brain activation between students with dyslexia and their typical counterparts, albeit the research in adult population is rather limited. In this study, we examined the brain activation differences between 14 typical and 12 university students with dyslexia. The two tasks consisted of words having different degrees of auditory and visual distinctiveness. The whole procedure was recorded with a 14-sensor sophisticated EEG recording device (Emotiv EPOC+). The findings from the auditory task revealed statistically significant differences in the left temporal and occipital lobe and in the right prefrontal area. Concerning the visual task, differences were evident again in the left temporal and occipital lobe, in the parietal lobe and in the right occipital lobe. The findings indicate differences in the hemispheric brain activation of students with or without dyslexia in various rhythms in both experimental conditions, shedding light in the neurophysiological discrepancies between the two groups. They also lay great emphasis on the necessity of carrying out more studies in adult population with dyslexia.

Keywords: dyslexia, EEG, magnocellular theory, audiovisual recognition, university students.

1. INTRODUCTION

Dyslexia is one of the most frequent specific developmental learning disorders, affecting 5–15% of school-aged children although estimates vary widely depending on the language and culture (American Psychiatric Association, 2013). It is related to severe deficits in reading and spelling skills which often co-occur with dysfunctional phonological processing (Snowling, 2000), difficulties in phonological representations and short-term memory deficits in coding, storing and retrieving these representations (Gathercole & Baddeley, 2014) that commonly persist in adult life (Paulesu et al., 2001).

According to recent studies, normal and readers with dyslexia differ in terms of processing visual and auditory information, as the large cell visual pathway of dyslexics, presents some form of abnormality or dysfunction (Stein, 2001).

2. BACKGROUND

2.1. Theoretical background

Livingstone and Galaburda (1993), concluded that the magnocellulars of the Central Nervous System of people with dyslexia were smaller in size and more disorganized compared to the ones of typically developed people. This was later confirmed in an in-vivo study by Giraldo-Chica, Hegarty, & Schneider (2015), where in the left lateral geniculate nucleus of the 13 subjects with dyslexia the magnocellular layers were significantly thinner than those of the subjects without dyslexia. This functional asymmetry is unknown but is certainly consistent with the magnocellular theory supporting that the visual magnocellular system is not developed normally in individuals with dyslexia. Livingstone and Galaburda (1993) also argued that in people with dyslexia the abnormalities in the magnocellular pathway affect the speed of processing visual information, even though the subjects do not have anything abnormal in their vision or optic nerve, resulting in processing visual information at a slower rate than the majority of people.

Stein, Talcott, and Walsh (2000) report that the magnocellular region of the visual system, which is a complementary region of the visual cortex and important for the perception of time, visual events, and control of eye movements, appears to be dysfunctional. This inadequate control of eye movements may lead to unstable vision. The control of eye movements is largely dependent on magnocellular signals. Therefore, the relative insensitivity of individuals with dyslexia to visual movement significantly affects their eye movement control (Kirkby, Webster, Blythe, & Liversedge, 2008), compromising the accuracy of their eye fixation (Fischer & Hartnegg, 2000).

The magnocellular theory of dyslexia has also been combined with the auditory deficit hypothesis (Stein, 2001). According to this hypothesis, it is argued that individuals with dyslexia also exhibit abnormalities in their auditory system, which are due to anatomical abnormalities in the magnocellular pathway. Thus, people with dyslexia have difficulty perceiving low and complex sounds but perceive higher pitched and simple sounds better.

Consequently, several researchers conclude that the magnocellular theory is a unifying theory of both the cerebellar hypothesis and the visual or auditory hypotheses, or a generalization of the visual theory. On this basis, a general sensory magnocellular abnormality that leads to difficulties in processing sensory information, results in disruption of normal language learning and processing leading to learning difficulties (Stein, 2001).

In addition to visual and auditory deficits, the magnocellular deficit theory also explains the cerebellar deficit in dyslexia (Stein, 2001). Considering that the cerebellum receives information from the magnocellular system, the cerebellum is also affected by a general magnocellular dysfunction.

2.2. Neuroimaging studies

2.2.1. EEG waves

In several studies over the last 20 years, electroencephalograph (EEG) has been used to study the physiology of the brain in patients with dyslexia, as it is non-invasive, painless, cheap and potentially wearable to record electrical activity of human brain from the scalp surface (Xing, Mccardle, & Xie, 2012). EEG measures brain waves of different frequencies within the brain. A frequency is the number of times a wave is repeated in one second. If any of these frequencies are insufficient, excessive, or difficult to access, our mental performance can suffer. EEG is usually described in different frequency bands: Gamma (γ) is greater than 30Hz, Beta (β) (13-30Hz), Alpha (α) (8-12Hz), Theta (θ) (4-8Hz), and Delta (δ) (less than 4Hz) (Perera, Shiratuddin, & Wong, 2018).

2.2.2. EEG studies

Most studies focusing on EEG rhythms' changes have employed tasks associated with reading difficulties. For example, Rippon and Brunswick (2000) found that children with dyslexia showed increased frontal θ activity in a phonological task, whereas no differences were observed between the dyslexic and the control group in a visual task. In addition, there was a marked increase in β rhythm activity in the right parietal-occipital area in children with dyslexia when performing a phonological compared to a visual task (Papagiannopoulou & Lagopoulos, 2016). Studies (Perera et al., 2018) comparing individuals with dyslexia and individuals with good literacy skills concluded that children with dyslexia show greater consistency in δ, θ, and β rhythms while showing lower consistency in α frequencies during relaxation. In addition, EEG coherence in different frequency bands plays a different role each time. In a study during an audiovisual attention task (Dhar, Been, Minderaa, & Althaus, 2010), reduced and diffuse intrahemispheric coherence of α activity was found in the central-brain cortex. Coherence of β and γ rhythms has been linked to more complex linguistic sub-processes, such as syntax or semantics. EEG findings from the literature study show increased (left) frontal and right temporal slow activity in the δ and θ bands and increased β in F7 (Kandel, Lassus-Sangosse, Grosjacques, & Perret, 2017).

Studies have documented low brain activation in a variety of brain regions in adults with dyslexia. Steinbrink, Groth, Lachmann, and Riecker (2012) during phonological and temporal processing tests, found lower activation in the insular cortex in patients with dyslexia than in the control group. Peyrin et al. (2012) during a phonological test in adults with dyslexia, observed reduced activation of the left inferior angular gyrus. Pecini et al., (2011) observed reduced activation in the frontal network of the left hemisphere associated with phonological working memory in individuals with dyslexia and a history of delay in language development.

Adults with dyslexia have also been found to show increased activation of the left inferior frontal gyrus during phonological tests (Dufor, Serniclaes, Sprenger-Charolles, & Démonet, 2009). Similarly, McCrory, Mechelli, Frith, & Price, (2005) during a reading test, found significantly reduced activation of the left occipital area. Karni, Morocz, Bitan, Shaul, & Breznitz (2005) during a slow pseudoword test, found a different pattern of brain activity. The left frontal gyrus (Broca's area) is activated in readers with dyslexia, while the control group shows activation in the visual areas of the left extrastriate cortex.

A number of methods has been proposed in order to measure EEG signals in several populations through brain computer interface (BCI). One such device is the lightweight Emotiv EPOC+ wireless EEG system which has received the most empirical attention in a spectrum of different fields (Badcock et al., 2015). Concerning the exploration of the relationship between several forms of learning difficulties and EEG abnormalities there have been just a handful of researches using the Emotiv EPOC+. Eroğlu, Aydın, Çetin, and Balcisoy (2018) found that the dyslexic group showed significantly lower complexity at the lowest temporal scale and at the medium temporal scales than the control group.

3. METHODOLOGY

3.1. Objectives

The purpose of this study is to investigate the brain function of young adults with dyslexia through innovative and non-invasive methods of functional imaging of the brain in phonological and morphological awareness tests, such as audiovisual discrimination tasks in a word-level. The main research hypotheses that have been formulated for investigation are the following:

- Whether the brain area activation through EEG signal recording (dependent variable) is correlated between students with and without dyslexia during the experimental condition of auditory discrimination
- Whether the brain area activation through EEG signal recording (dependent variable) is correlated between students with and without dyslexia during the experimental condition of visual discrimination

3.2. Data acquisition

The sampling strategy used in this study is stratified random sampling. A history was taken from all participants where general information such as educational level, occupational status as well as their native language was recorded, as well as more specific information about their educational background, i.e. whether they attended an inclusion class or received speech and language therapy intervention. Information was also provided on any behavioral problems during school age through a brief psychosocial history. At the end of the procedure each participant received a certificate of participation.

In this study, 26 right-handed young adults (mean average 21.32 y/o) participated in this experiment, forming the Dyslexic group (12 students) and the Control group (14 students). All the subjects with dyslexia had undergone intervention at young age without reporting any dyslexia-related comorbidities. There were no major age or education-level differences since all of them were university students in the School of Health Sciences. Written consent forms to participate in this study were obtained from all the subjects who participated on a voluntary basis. The recording was terminated as soon as a participant felt any discomfort with the device or the procedure. Each experimental session lasted 22 minutes on average depending on the time required by the participants to answer each question.

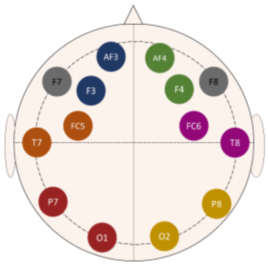
3.2.1. Software

For the purposes of the research, a software was created which was used for the electronic presentation of the visual and auditory stimuli in the phonological test. The software runs in the Android environment in the form of an application and was created by a computer consultant using the Android Studio tool. This software, called "Dyslexia", can be used as an application on smart Android devices and also on Windows computers after installing the Bluestacks platform. Bluestacks is a tool that simulates the Android environment and allows the installation of applications locally on the computer.

3.3. EEG acquisition

For the EEG recordings, the BCI device Emotiv EPOC+ head-set was used, a wireless neuro-signal acquisition device with 14 wet sensors (+2 reference), capable of detecting brainwaves at 128Hz sequential sampling rate. The participants were seated in a comfortable chair in front of a computer screen and a specialized technician set up the device following the instructions provided by the EmotivPRO Software, regularly checking the quality of the connectivity in the beginning and during the recording. The felt pads were placed in the scalp according to the International 10-20 System (AF3, F3, F7, FC5, T7, P7, O1, AF4, F4, F8, FC6, T8, P8 and O2), using saline liquid solution on all felt pads of each sensor (Figure 1). However, due to loss of connectivity the F8 electrode was isolated and rejected and so was the corresponding channel, F7 to maintain the symmetry of the recording.

Figure 1.
Regions of Interest according to the electrode sites. (Blue: Left frontal, Orange: Left temporal, Red: Left occipital, Green: Right frontal, Purple: Right temporal, Yellow: Right occipital, Grey: Rejected channels).



The recordings were made with the montage, according to the connected mastoids, and the EEG signals were saved in ".edf" format. A Butterworth notch filter is applied to remove 50 Hz power line noise oscillations from EEG signals and a 0.5 Hz high-pass digital FIR filter to remove low frequency oscillations. Next, five FIR filters of similar design are designed to allow frequencies within a certain range and attenuate frequencies outside that range. The five bandwidth filters (δ ≈ 0.5-4Hz, θ ≈ 4-8Hz, α ≈ 8–12Hz, β ≈ 13– 30Hz, and γ ≈ 30-60Hz) are designed in relation to the 5 EEG rhythms, trying to export spectral characteristics to each sub band of frequencies to be investigated. In more detail, these frequency characteristics were exported to each zone and the normalized value (ranging from 0 to 1) was calculated for each characteristic, so that comparisons between the two groups would be more efficient. Specifically, the normalized value was calculated through the following formula:

$$Energy = \sum_{j=1}^{N} x^2 \ , \ i = \delta, \theta, \alpha, \beta, \gamma$$

The whole analysis was conducted on the following RoI (Regions of Interest) consisting of different sample sizes between students with dyslexia (DYS) and the control group (CON):

- Whole brain (AF3, F3, FC5, T7, P7, O1, AF4, F4, FC6, T8, P8 and O2) (DYS = 5, CON = 6)
- Left hemisphere (AF3, F3, FC5, T7, P7, O1) (DYS = 7, CON = 8)
- Right hemisphere (AF4, F4, FC6, T8, P8 and O2) (DYS = 7, CON = 11)
- Left frontal lobe (AF3, F3) (DYS = 11, CON = 9)
- Left temporal lobe (T7, FC5) (DYS = 9, CON = 14)
- Left occipital lobe (O1, P7) (DYS = 9, CON = 13)
- Right frontal lobe (AF4, F4) (DYS = 7, CON = 13)
- Right temporal lobe (T8, FC6) (DYS = 12, CON = 12)
- Right occipital lobe (O2, P8) (DYS = 12, CON = 14)

3.4. Material

The material included in the software consists of 60 triads of words, which have been selected meeting strict phonological, morphological, and semantic criteria taking into account the difficulties encountered by people with dyslexia as reported in the international literature (Asvestopoulou et al., 2019). Participants' performance was evaluated with a novel interactive application measuring audiovisual discrimination of words in two experimental conditions.

3.4.1. Phonological criteria

The material presented in the two experiment tasks followed several predefined phonological, morphological and semantic criteria based on common errors in Greek made by people with dyslexia, especially focusing on confusing letters with visual (κ, γ, χ) or auditory similarity (f, v, θ, ð) (Kalantzi-Azizi & Zafeiropoulou, 2004). Also, the word material evaluated in this experimental procedure, had target phonemes located in initial, middle and final positions. The first categorization of the phonological criteria involved the division of errors into structural and spelling errors. More specifically, the structural errors considered in this research concerned simplifications of phonemes (f, v, θ, ð), in which people with dyslexia show a higher frequency of errors such as: phonemes substitution, shift, and omission.

3.5. Auditory discrimination task

In the first experimental auditory discrimination task, participants were asked to differentiate verbally-presented words containing phonemes with common phonological characteristics (eg fo΄vame, fo΄ðame, fo΄θame). Participants saw 3 boxes with written numbers in a row on a computer screen, asking them to choose the number that corresponded to the word they thought was correct in a predefined time limit of 10 seconds. The verbal instruction given was the following: "choose the right word you hear".

3.6. Visual recognition task

In the second experimental task, which assessed visual recognition, the participants saw 3 words in a row on the screen, and had to implicitly read them as carefully as possible choosing the one that they thought had the correct spelling in a time limit ranging from 5 to 10 seconds. The on-screen instruction was: "Choose the right word you see".

4. RESULTS

Aiming to examine the correlation of brain regions and waves through EEG recordings between the two sets of groups (control and dyslexic) in (i) auditory discrimination and (ii) visual recognition of words, we performed t-tests as the data were checked and found that they are approximately normally distributed. No multiple t-tests were performed, as each one of them concerned a specific brain region and wave.

(i) Regarding the auditory discrimination task we observed statistically significant differences in both hemispheres. More specifically, in the left hemisphere differences were found in the left temporal lobe in β (p=.005), γ (p=.002) and δ (p=.017) rhythms, in the left occipital lobe in β (p=.02), rhythm, and in the right prefrontal area in α (p=.02), β (p=.05) and γ (p=.04) rhythms, respectively. Students with dyslexia reported higher mean scores only in δ rhythm in the left temporal lobe, and in α, β and γ rhythms in the right prefrontal area of the hemisphere (Table 1).

Table 1.
T-test examining the correlation of brain regions and rhythms between Control and Dyslexic groups in Auditory discrimination task.

	Control (n=14)		**Dyslexic (n=12)**		**df 25**	
	Left Hemisphere					
	M	Sd	M	Sd	t	Sig
T7_δ	0.556	0.234	0.771	0.100	-2.585	**.017**
T7_β	0.113	0.082	0.032	0.014	2.890	**.005**
T7_γ	0.133	0.093	0.031	0.015	3.255	**.002**
O1_β	0.091	0.031	0.054	0.027	2.487	**.027**
	Right Hemisphere					
AF4_α	0.014	0.011	0.029	0.014	-2.569	**.020**
AF4_β	0.020	0.014	0.052	0.024	-3.758	**.005**
AF4_γ	0.026	0.088	0.047	0.114	2.223	**.040**

(ii)Concerning the visual task, statistically significant differences were evident in the left temporal lobe in β (p=.02), γ (p=.04) rhythms, in the occipital lobe in α (p=.01), β (p=.01) and δ (p=.02) rhythms, in the left parietal lobe in β (p=.02) rhythm, and in the right occipital lobe in δ (p=.01), β (p=.01) and γ (p=.03) rhythms. The students with dyslexia reported higher mean scores only in the δ rhythm of both the left and right occipital lobe (Table 2).

Table 2.
T-test examining the correlation of brain regions and rhythms between Control and Dyslexic groups in Visual recognition task.

	Control (n=14)		**Dyslexic (n=12)**		**df 25**	
	Left Hemisphere					
	M	Sd	M	Sd	t	Sig
T7_β	0.142	0.088	0.064	0.060	2.334	**.020**
T7_γ	0.170	0.111	0.080	0.081	2.090	**.040**
O1_δ	0.420	0.132	0.595	0.206	-2.499	**.021**
O1_α	0.045	0.018	0.034	0.011	2.567	**.011**
O1_β	0.106	0.025	0.068	0.039	2.813	**.010**
P7_β	0.140	0.076	0.079	0.048	2.121	**.032**
	Right Hemisphere					
O2_δ	0.355	0.152	0.538	0.205	-2.612	**.015**
O2_β	0.123	0.041	0.028	0.019	3.136	**.011**
O2_γ	0.131	0.106	0.090	0.062	2.280	**.033**

5. DISCUSSION

The aim of this study was to track brain activity in the regions of interest, testing differences in brain rhythms as they were recorded through a BCI device (Emotiv EPOC+), between young adults with dyslexia and a control group across two experimental conditions (auditory discrimination and visual recognition). Although such sophisticated, light-weighted and wearable device has been employed to record EEG signals aiming to analyze dyslexia-related RoI in children population (Eroğlu et al., 2018), this is the first study using a BCI device in adults, indicating the potential of such a lifestyle device to evaluate differences in brain activation among typically developed adults and age-matched subjects with learning disabilities.

The findings in both experimental conditions are in line with previous researches reporting a left occipito-temporal hypoactivation converging on the same brain regions associated with the reading deficit (Paulesu, Danelli, & Berlingeri, 2014).

5.1. Auditory discrimination task

The findings indicated statistically significant differences in brain regions in both hemispheres between the two groups, revealing the heterogeneity of rhythm activation in different regions (Perrachione et al., 2016). More specifically, in the left temporal and occipital regions and the right frontal region, students with dyslexia had higher activation in rhythms δ and α, while they had lower activation in rhythms θ, β, and γ. Furthermore, the presence of this finding in the left temporal region, which is considered as the main neural area responsible for sound-based phonological representations (Buchsbaum, Hickok, & Humphries, 2001), demonstrates the difficulty of these individuals to make correct auditory word discrimination. Consistent with the results of Gori, Seitz, Ronconi, Franceschini, & Facoetti (2015) and Kandel et al. (2017), these findings enrich the hypothesis that left temporal low activity reveals a strong interaction between auditory processing difficulties and reading impairments.

Regarding the lower activation of θ and β rhythms, a possible interpretation comes from Spironelli and Angrilli (2018), who report that β rhythm activation is not well developed in children, while in adults the relative contribution of spectral β activation is reversed.

The common finding in the left hemisphere and left temporal lobe of a lower β rhythm activation as recorded in students with dyslexia probably suggests impairments in active thinking, active attention, and concentration for problem solving in these individuals (Zakopoulou et al., 2019). Also, the lower β rate in the left occipital region may be associated with an inability to rapidly process auditory information, while in contrast, recording a higher β rate activation in the right prefrontal and frontal regions may indicate an increase in anxiety or a decrease in the degree of relaxation.

5.2. Visual recognition task

In the second experimental condition in which participants' visual recognition skill at the word level was assessed, statistically significant differences were found in both right and left hemisphere areas. This finding is confirmed by similar studies where differentiation of motor and sensory information between the two hemispheres was observed in individuals with dyslexia (Zakopoulou et al., 2019). These developmental changes or asymmetries in the neural network of brain structures may form the basis for the interpretation of sensory and cognitive problems in dyslexia.

Another important finding is that a lower activation of β and γ rhythms in the occipital region of both the right and left hemispheres was observed, thus, revealing that the smaller and disorganized magnocellulars in the occipital cortex responsible for activating the movement of visual stimuli may be underactive (Kelly & Phillips, 2016), thereby explaining the reduced performance in the corresponding test of visual recognition.

An interesting finding is the under-activation in dyslexic students in the β rhythm in the parietal region of both the right and left hemispheres, respectively. The left parietal lobe is thought to be involved in phoneme-grapheme correspondence (Bitan et al., 2007), and also forms the bridge of phonological and articulatory representations (Paulesu et al., 2001).

What is evolutionary in this study, is the attempt to further investigate the rhythms' activation within these brain regions, where students with dyslexia exhibited lower β and γ rhythms in the left occipito-temporal lobes, during both auditory and visual tasks, suggesting that these rhythms are linked with difficulties in the phonological and reading processes as well as with failure of left posterior brain systems (Shaywitz et al., 2002). Similarly, a reduced α activity in the left occipital region was found only during the visual task, indicating a relationship between α rhythm, cognitive performance (Riviello, Nordli, & Niedermeyer, 2011), and brain maturation (Pineda, 2005).

Interestingly, during the auditory task an increased δ rhythm was found in the left temporal region, while similarly high δ rhythm was found in the left occipital region during the visual task. Being in line with Gori's (Gori et al., 2015) and Kandel's (Kandel et al., 2017) results, these findings enrich the assumption that the left occipito-temporal slow activity reveal a strong interaction between auditory processing difficulties and reading impairments.

5.3. Study limitations

A key limitation of the study is the relatively small sample of participants that formed the two research groups (12 students with dyslexia and 14 control students), although in medical and educational research the number of subjects is limited (Frid & Breznitz, 2012). Therefore, the small sample may pose limitations to the generalizability of the results, however, it does not diminish their significance as they are derived from a complex form of multivariate analyses.

In addition, the absence of signal recording during the resting state which could have been recorded, might have caused fatigue in the participants, thus compromising the reliability of the results. Nevertheless, these limitations provide an incentive for researchers to administer the survey to a larger sample, including an additional experimental condition in future research.

6. CONCLUSION

Alpha, beta and delta EEG bands defined unique brain activations and related possible phonological and reading impairments, in adults with dyslexia, during auditory and visual tasks. Evidence that underpins the theory of magnocellular processing, which postulates the coexistence of auditory and visual processing deficits as indicative of a broadly distributed dysfunction in the "neural signature" of dyslexia.

Furthermore, the findings of the current study confirm the heterogeneity of the rhythm activation in different regions between the two groups.

Interestingly, the heterogeneous activation patterns of delta, theta, beta and gamma rhythms in the occipital, temporal and parietal lobes respectively during auditory and visual word recognition tests, emphasize the necessity of a multifactorial approach to dyslexia at the level of diagnosis and intervention, even in adult individuals with dyslexia (Prestes & Feitosa, 2016).

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