

## Chapter #7

### RESTING STATE EEG POWER ANALYSIS IN FILIPINO CHILDREN WITH DYSLEXIA

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#### ABSTRACT

Dyslexia is a neurodevelopmental disorder characterized by severe and persistent reading difficulties despite normal intellectual functioning and appropriate schooling. To better understand the neural underpinnings of dyslexia, this study investigated the neurophysiological differences between normal readers (NR group, n = 4) and readers with dyslexia (DYS group, n = 5) by analyzing their brain activity at eyes-closed resting state using mobile electroencephalography (mobile EEG). The results revealed that the *DYS* group exhibited an overall larger power activation in the theta and beta frequency bands, as well as a dominance of delta, theta, and beta frequencies across all scalp sites. Increased delta and theta activity was found in the left frontal region, whereas significantly stronger beta power was found in the right hemisphere. Moreover, weaker alpha activity was observed in the left frontal and right posterior regions. These findings provide evidence of an atypical and less integrated linguistic network in dyslexia.

*Keywords:* dyslexia, reading, mobile EEG, resting state.

## 1. INTRODUCTION

### 1.1. Dyslexia

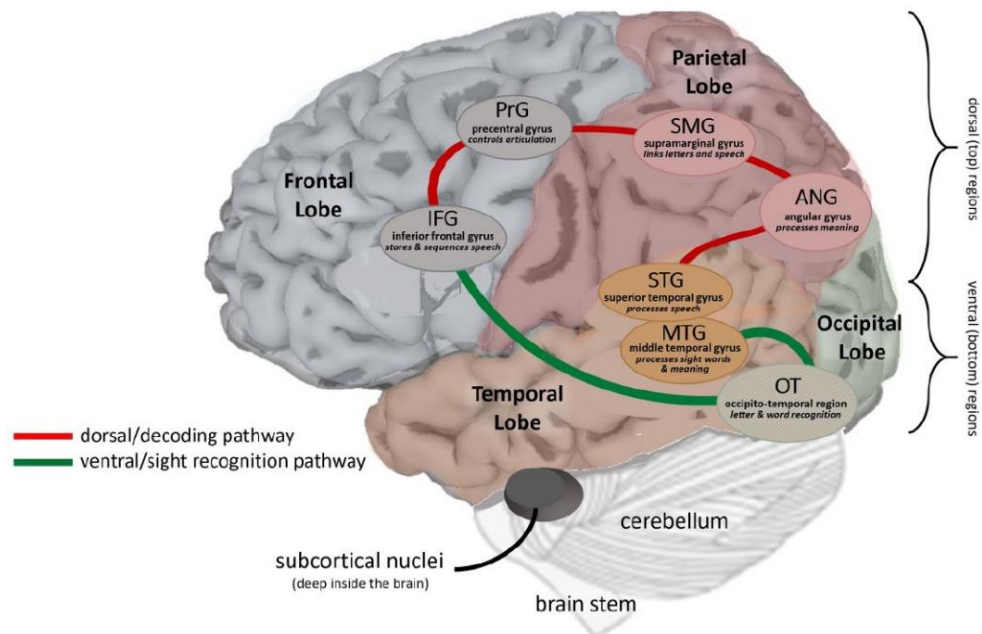
Dyslexia is a neurodevelopmental disorder characterized by severe and persistent reading deficits in both children and adults despite normal intellectual functioning and having been provided with educational opportunities (Pina Rodrigues et al., 2017). Over the years, dyslexia has been examined carefully and intensively by researchers who have attempted to determine its genetic, neurobiological, and cognitive components (Snowling, 2013). Although dyslexia is usually only diagnosed after two to three years of schooling, neuroanatomical precursors have been identified in pre-reading children at family risk for the disorder (Goswami, Power, Lallier, & Facoetti, 2014; Raschle, Zuk, & Gaab, 2012; Clark et al. 2014). Indeed, dyslexia is both familial and heritable, with family history as one of the most important risk factors. There is substantial evidence derived from twin and family studies for the genetic factors of dyslexia (Olson et al., 2013), and these findings have educational implications. That is, if a child has a parent or a sibling with dyslexia, it is important that the child is carefully observed for signs of reading difficulties (Caylak, 2010; Shaywitz & Shaywitz, 2008).

### 1.1.1. Neurobiology of reading and dyslexia

A number of interrelated neural systems, primarily located in the left hemisphere, are involved in reading (Shaywitz & Shaywitz, 2008). The *dorsal system* involves phonologically-based reading and facilitates grapheme-phoneme conversions. This network constitutes the left dorsal temporo-parietal circuit around Wernicke's area and includes the posterior superior temporal gyrus and the inferior parietal lobule. Next, the *ventral system*, which is associated with visual-orthographic word recognition, involves the left ventral occipito-temporal circuit, consisting of the lateral extrastriate, fusiform, and inferior temporal regions where the visual word form area (VWFA) is found. Finally, the *anterior system* facilitates speech articulation and word analysis, and includes the left inferior frontal circuit around Broca's area consisting of the inferior frontal and precentral gyri (Martin, Schurz, Kronbichler, & Richlan, 2015; Richlan, 2014).

Figure 1.

The cortical reading framework (Kearns, Hancock, Hoeft, Pugh, & Frost, 2019).



In learning how to read, children must be able to transform visual symbols (graphemes) into their corresponding units of sound (phonemes). A very critical portion of the brain involved in this process is the posterior brain region, which is comprised of the angular gyrus and supramarginal gyrus in the inferior parietal lobule, as well as the posterior aspect of the superior temporal gyrus. Readers with dyslexia experience a disruption in these areas which requires compensation in the anterior region, including the inferior frontal gyrus and right posterior areas playing an important role in speech articulation. This anterior system is believed to help readers with dyslexia develop an awareness of the sound structure of the word by forming the word with their lips, tongue, and vocal apparatus, allowing them to read albeit very slowly and inefficiently. The posterior system, which includes the right occipito-temporal region, facilitates visual pattern recognition, thereby compensating for the impaired word analysis that occurs in the left posterior regions.

## 1.2. EEG

In the field of neurodevelopmental research, traditional neuroimaging modalities such as electroencephalography (EEG) have a long and productive history (Loo, Lenartowicz, & Makeig, 2015; McLoughlin, Makeig, & Tsuang, 2014). EEG is the oldest non-invasive tool to record human brain activity by means of capturing summed electrical field activity (measured in voltage) produced by pyramidal cortical neurons that are aligned parallel to the scalp, allowing the investigation of brain responses to external stimuli (Lau-Zhu, Lau, & McLoughlin, 2019). EEG data are commonly analyzed in terms of brain frequencies which are obtained using data extraction techniques (i.e., extracting frequency bands, usually between 1–70 Hz). These frequency bands range from low to high: delta ( $\delta$ ; 0–4.0 Hz), theta ( $\theta$ ; 4–8 Hz), alpha ( $\alpha$ ; 8–12 Hz), beta ( $\beta$ ; 12–25 Hz), and gamma ( $\gamma$ ; 25–100 Hz).

Despite its poor spatial resolution, EEG has excellent temporal resolution in the order of milliseconds, thereby permitting the examination of fast neuronal dynamics in the brain. Traditional EEG systems present one major limitation: They are restricted to the laboratory due to heavy amplifiers and an extensively wired system with many cables and connections, which can limit its potential to study a variety of processes with a wide range of populations and address research questions (Lau-Zhu et al., 2019). Other disadvantages include lack of mobility and high cost of equipment (Nooner & Kerupetski, 2017). Meanwhile, the last decade has witnessed the rapid development of novel brain imaging tools and among these is mobile electroencephalography (mobile EEG), which allows researchers to flexibly record real-time brain activity (de Vos & Debener, 2013).

### 1.2.1. Mobile EEG

Several terms are associated with mobile EEG – portable, wearable, wireless, and dry – and they all highlight the flexibility and convenience it offers (Poulsen, Kamronn, Dmochowski, Parra, & Hansen, 2017; Wascher et al., 2016). Commonly involved in a wide range of consumer-oriented applications such as motor imagery (Lopez-Gordo, Perez, & Minguillon, 2019), gaming control (Cattan, Mendoza, Andreev, & Congedo, 2018), sleep monitoring (Baron et al., 2018; Burgdorf et al., 2018), ‘brain training’ (Kimura & Okuda, 2018; Olfers & Band, 2017), and sports performance enhancement (Park, Fairweather, & Donaldson, 2015), rapid developments and dramatic changes continually take place to further promote its utility as a research-grade system that is suited to medical and scientific research (Rough, Chapman, Bartolomeo, Gonzalez, & Strauss, 2019). Eventually, researchers in the field of neuroscience began to perceive mobile EEG as a more accessible form of neurotechnology that can obtain information about underlying neural processes in a quick and expedient manner. Furthermore, several academic journals have even released special issues dedicated to the efficacy of mobile EEG as a neuroscientific tool.

**Why Mobile EEG?** Whereas traditional EEG systems have incredibly complex laboratory based set-ups, mobile EEG devices are ‘wearable’ wherein participants are free to stand up and walk at any point during recordings (Bateson, Baseler, Paulson, Ahmed, & Asghar, 2017). Recent developments have led to the use of dry electrodes which reduces preparation time and eliminates the need to apply conductive gel or a saline patch that is typically required in traditional EEG (Liao et al., 2012). Moreover, mobile EEG has proven to be flexible and convenient for task stimuli presentations on computers and laptops (Soto et al., 2018), smartphones and tablets (Debener, Emkes, De Vos, & Bleichner, 2015; Griffiths, Mazaheri, Debener, & Hanslmayr, 2016), and augmented-reality eyewear (Duvinaige et al., 2013). For pediatric populations, mobile systems minimize both equipment burden and burden on participants and their families from travelling by allowing testing in convenient locations such as homes and schools (Lau-Zhu et al., 2019).

**Mobile EEG as an assessment tool for dyslexia.** Mobile EEG has been considered to be an excellent candidate as a quantitative neurobiological measure that is much more feasible and less expensive than other neuroimaging modalities, including traditional EEG and magnetic resonance imaging (MRI) (Loo et al., 2015). An increasing number of studies looking into the functionality of mobile EEG have considered its suitability for children with neurodevelopmental disorders, especially dyslexia.

Dyslexia is a complex, multifaceted disorder that impacts brain function across the lifespan and it is unlikely that different children with dyslexia manifest the same clinical presentation (Snowling, 2013; van der Leij, 2013). Although a plethora of studies have reported that dyslexia is caused by impaired phonological awareness (Goswami et al., 2014; Goswami, 2016; Pammer, 2014; Ramos, 2013), there is an increasing amount of evidence that supports the possibility of a core visual deficit (Bogon, Finke, & Stenneken, 2014; Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012, Franceschini et al., 2013; Gabrieli & Norton, 2012; Giovagnoli, Vicari, Tomassetti, & Menghini, 2016). Given the complex nature of dyslexia, there is a need for brain-based assessments that can directly identify each child's strengths and weaknesses and develop specialized treatments to address individual issues. Whereas current methods of brain-based assessments are generally costly and not widely available, an increasing number of researchers are realizing the potential of mobile EEG as a means to bring these to schools and the community. However, more research is needed to examine whether research-grade mobile EEG systems can outweigh investment in a traditional EEG lab, and if signal quality can be maintained in these systems as they are used on neurodevelopmental populations.

### **1.3. Resting State EEG**

One approach to understanding dyslexia is through analyzing resting state activity, an area of interest in cognitive neuroscience wherein intrinsic functional connectivity at rest permits the brain to allocate resources and prepare itself for changes stemming from the internal or external environment. This allows researchers to make predictions about the resting state network as a determining factor of underlying neural activity. Research in this area has provided valuable evidence on deviant network organization for neurological disorders and generated much understanding about the neural characteristics of healthy brain development (Alcauter et al., 2017; Gracia-Tabuenca, Moreno, Barrios, & Alcauter, 2018).

#### **1.3.1. Resting state EEG studies on learning disorders**

Typically, a resting state EEG experiment involves the participant wearing the EEG device for a period of minutes, at rest, and with no specific external stimuli. Prior to the experiment, the researcher provides the participant with instructions to relax and be still during the recording. This approach allows researchers to assess which brain regions are most active when no external tasks demand attention (Duncan & Northoff, 2013). Moreover, the eyes-closed resting state condition eliminates the impact of confounding factors, such as of visual noise, experimental tasks, fatigue, task-related anxiety, and other experiences that are associated with external task performance (Duncan & Northoff, 2013). Of course, care should be taken to minimize sources of these factors as the aim of the resting state EEG experiment is to obtain measures of "true," "pure," and unbiased baseline brain activity (Shephard et al., 2018). By studying resting state activity in children with dyslexia, we can determine underlying processing difficulties in the left reading and language network. These disruptions are characterized by functionally disrupted connectivity patterns and slower spontaneous neural activity, which are correlated with reading problems in dyslexia (Schiavone et al., 2014).

At resting state, learning disorders are characterized by greater theta activity which is reflective of cortical hypoactivation (Alahmadi, 2015; Lenartowicz & Loo, 2014; Lenartowicz, Mazaheri, Jensen, & Loo, 2018; Roca-Stappung, Fernandez, Bosch-Bayard, Harmony, & Ricardo-Garcell, 2017; Rommel et al., 2017; Woltering, Jung, Liu, & Tannock, 2012). This prevalence of slow oscillations serves as the basis of the “maturational delay hypothesis” wherein a maturational delay in brain structure leads to deviant neural functioning in children with learning disorders (Jäncke & Alahmadi, 2016). Resting state EEG studies on dyslexia generally indicate remarkably elevated low frequency activity in the left hemisphere which reflects a less integrated language network (de Vos, Vanvooren, Vanderauwera, Ghesquière, & Wouters, 2017; Fraga González et al., 2016; Pagnotta et al., 2015; van der Mark et al., 2011). A study by Roca-Stappung and colleagues (2017) reported the presence of greater delta and theta power as well as weaker alpha and beta power in children with dyslexia and other learning disorders. Likewise, Papagiannopoulou and Lagopoulos (2016) applied global and region-by-region analyses to examine hemispheric asymmetry in closed eyes resting state EEG. Their findings confirmed the existence of an atypical linguistic network that is characterized by a dominance of theta power in the left frontal regions, implicating the presence of brain abnormalities in children with dyslexia prior to reading acquisition. In a study by Farris et al. (2011), children with dyslexia were found to have reduce connectivity between the left and right inferior frontal gyri, which are crucial for both reading and listening comprehension. Analyzing both resting state and syllable processing using intra-cortical power spectra EEG, Morillon, Liégeois-Chauvel, Arnal, Bénar, and Giraud (2012) found that stronger theta power in the right hemisphere and low gamma power in the left hemisphere, suggesting that left-hemispheric regions sample and integrate acoustic information at a gamma rate, whereas right-hemispheric regions do so at a theta rate. At rest, higher theta power dominance was detected in the left hemisphere as compared to the right hemisphere. Moreover, Babiloni et al. (2012) found abnormal alpha rhythms, whereas a number of studies have observed abnormally stronger beta power in the right hemisphere, indicating task-related overexcitability (de Vos et al., 2017; Dimitriadis, Laskaris, Simos, Fletcher & Papanicolaou, 2016; Dimitriadis, Simos, Fletcher, & Papanicolaou, 2018; Hoefl et al., 2011; Jiménez-Bravo, Marrero, & Benítez-Burraco, 2017; Lizarazu et al., 2015; Power, Colling, Mead, Barnes, & Goswami, 2016; Simos et al., 2011).

## **2. RESEARCH OBJECTIVES**

Using mobile EEG as a research tool, this study was aimed at measuring differences in resting state EEG power between normal reading children and children with dyslexia. This study also illustrates the advantages of mobile EEG in studying resting state activity for children with dyslexia, such as its efficiency in data gathering and its less demanding set-up. Because mobile EEG is lightweight and more comfortable than the traditional EEG, it is more suitable for extensive periods of data collection. As children may find long assessments demanding, it will be easier for them to sit still and relax. Additionally, mobile EEG systems require a shorter preparation process of only five to 10 minutes. In this manner, it be less effortful for the researcher to collect high-quality EEG data.

## **3. DESIGN**

We utilized a non-equivalent control group posttest-only design. Also, purposive sampling was used wherein the selection of participants was based on predetermined criteria set by the researchers.

## 4. METHODS

### 4.1. Participants

Two groups participated in this study: the dyslexia (DYS) group and the normal reader (NR) group. For both groups, the following criteria were set: 1) Between ages 9 to 11 years; 2) Non-verbal IQ within the normal range (at least at the 75<sup>th</sup> percentile) as obtained from the Raven's Colored Matrices (Raven, Raven, & Court, 2003); 3) Normal vision (e.g., not wearing eyeglasses) as assessed by their respective physicians; 4) Right handed; and 5) Male. Specific to the DYS group, participants should be : 1) Enrolled in a special education school or center; 2) Have been previously diagnosed with Specific Learning Disorder with an impairment in reading by a professional (medical doctor or clinical/school psychologist); and 3) Should have no co-morbid disorders (i.e., attention-deficit/hyperactivity disorder, autism spectrum disorders, speech/language and visual impairments). For the NR group, an additional criterion is that the participants should not have any history of reading difficulties.

To decrease the possibility that the DYS group received formal reading intervention, a younger group was chosen. Also, right-handed participants were selected due to studies on handedness and cerebral lateralization indicating that right-handers have a remarkable advantage over left-handers in developing language and reading skills (Haberling, Badzakova-Trajkov, & Corballis, 2011; Vlachos & Bonoti, 2018).

*Table 1.*  
*Participants' characteristics according to group.*

	Dyslexia group (DYS group)	Normal reader group (NR group)
Number of participants	N = 5	N = 4
Mean age (in years)	9.61 (1.70)	9.61 (1.00)
Mean IQ	103.2 (5.72)	102 (5.83)
Years of schooling	6.4 (0.55)	6.5 (0.58)

### 4.2. Data gathering procedure

After the study was approved by the Ethics Review Committee of the University of Santo Tomas Graduate School, emails and letters describing the study's objectives, significance, and methodology were sent out to 14 schools and centers in Metro Manila. Among these, only three centers agreed to participate. Reading specialists from each center assisted the center administrators in selecting the participants using standardized achievement tests (e.g., Wide Range Achievement Test-4, Wechsler Individual Achievement Test-3). They also reviewed reports and other important documents from neurodevelopmental pediatricians and school psychologists that specify a diagnosis of dyslexia. After one month of screening, eight participants were selected for the DYS group. Three participants were eventually excluded from the study after their parents reported that aside from dyslexia, they also had a diagnosis of attention-deficit/hyperactivity disorder (ADHD). For the NR group, a total of four participants were selected by the center administrator of one tutorial center. After finalizing the selection of participants, we met with the parents to have a more thorough discussion of the study, to address any concerns, and to obtain informed consent prior to data gathering.

The experiment took place in a vacant classroom at the centers where the participants attend. The researcher specified beforehand that the rooms where the experiments were to take place should have no windows, and materials that were initially present inside the room (e.g., toys, books, drawings, pictures, and other fixtures on the wall) were removed to avoid distractions. The tables that were used for the experiment were placed against the wall and the researcher was seated to the right of the participant, far enough so as not to distract the participant from any movements. Data gathering was conducted individually for a total of 30 minutes including set-up. Prior to beginning the experiment, each participant was instructed to close his eyes and relax. They each completed a 5 minute eyes-closed resting state EEG recording. The researcher facilitated the experiment, while a research assistant monitored the recordings using a laptop. Data gathering was completed within a month.

### 4.3. Description of instruments

#### 4.3.1. Intelligence test

Raven’s Colored Progressive Matrices (CPM; Raven, Raven, & Court, 2003) was used to measure the non-verbal IQ of the participants by assessing their ability to perform perceptual matching, closure, symmetry, and reasoning by analogy. Designed for children ages 5 through 11 years, it consists of 36 items equally divided into three sets (A, Ab, and B) comprising of 12 items each. It can be administered within 30 minutes. The total score from the 36 items is computed by obtaining the sum of correct answers in the three sets. Participants who obtained a non-verbal IQ within the normal range (at least at the 75<sup>th</sup> percentile or an IQ of 90) were included in the study.

#### 4.3.2. Mobile EEG device

Brain signals were obtained by the Emotiv EPOC Neuroheadset (Emotiv Systems, Inc., 2013), a non-invasive, high-resolution, neuro-signal acquisition and processing wireless headset designed for contextualized research (see Figure 2). It has 14 channels (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF42) distributed according to the internationally accepted 10-20 system of electrode placement and includes two references in the CMS/DRL noise cancellation configuration P3/P4 locations. Only 12 channels were included in the study (i.e., T7 and T8 were excluded).

*Figure 2.*  
*The Emotiv EPOC Neuroheadset and its scalp locations.*



Data were transferred via Bluetooth to the computer and raw EEG signals were acquired using the EmotivPRO software. Using EEGLAB, signal processing was carried out wherein the recordings were segmented into epochs, which were then extracted and cleaned for artifacts. Power analyses were performed using fast Fourier transform for delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–25 Hz), and gamma (25–45 Hz). According to a number of validation studies, the EPOC has high accuracy and validity (Badcock et al., 2013, 2015; Bobrov et al., 2011; de Wit et al., 2017; Ousterhout & Dyrholm, 2013). In this study, the participants wore the EPOC headset throughout the experiment. Before putting on the headset, the 14 electrode recesses were fitted with a moist felt pad. If the pads were not already moist, saline solution was applied using a medicine dropper to carefully moisten the pads. The headset was then placed on the participant's head and subjected to software set-up. After verifying that the built-in battery was fully charged and the wireless signal reception was reported as good, the experiment began. Each participant wore the headset for an estimated total of 15 minutes.

#### **4.3.3. Mobile EEG software**

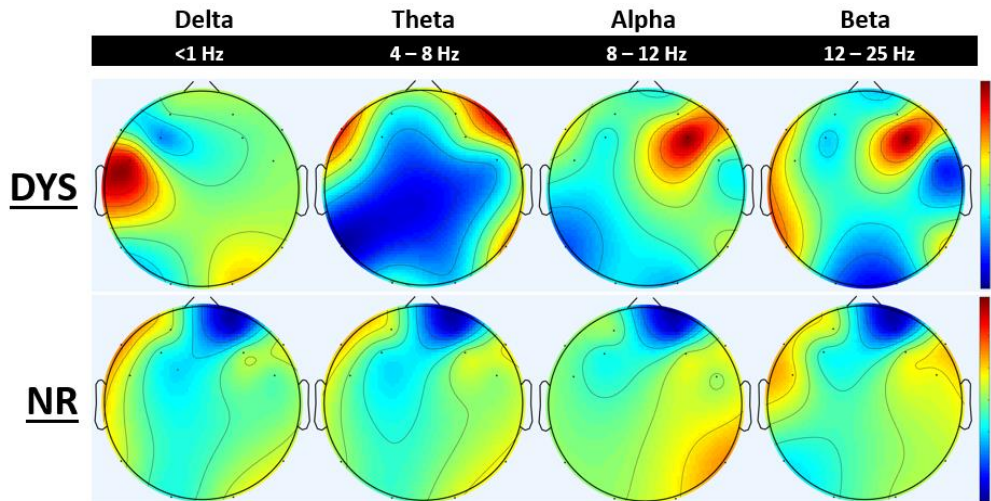
EmotivPRO (Emotiv Systems Inc., 2017) is an integrated software for neuroscience research and education, built for the EPOC headset. It features a real-time display of data streams including raw EEG, motion data, data packet acquisition and loss, and contact quality. Recordings, data streams, and frequency analyses are saved to a cloud storage where they are available for playback or export for analysis at any time. Frequency data were analyzed in two modes. Firstly, the Raw EEG data feature displayed the voltage fluctuations detected from each sensor on your headset. Secondly, the Fast Fourier Transform or Band Power feature performed a frequency analysis on single channel EEG data in real time or on recorded data. Moreover, EmotivPRO consisted of a control panel that displayed the contact quality of each electrode according to color: green for good signal, yellow for fair signal, orange for poor signal, red for very poor signal, while black meant no signal.

## **5. RESULTS**

Significant group differences were observed for the theta ( $U = 1$ ,  $p = .03$ ) and beta ( $U = 0$ ,  $p = .01$ ) frequency bands, wherein the DYS group exhibited overall stronger power for these bands. Tests comparing electrode sites indicate that the DYS group obtained significantly stronger theta power in the frontal and left parietal regions. Stronger beta power was mostly observed in the right frontal and left parietal regions. On the other hand, the NR group demonstrated stronger alpha power values in the left frontal and right occipital regions. Significant inter- and intra-hemispheric differences were limited to the delta, theta, and alpha bands (see Figure 3). For the DYS group, delta power is significantly left-lateralized in the frontal region, whereas theta power is bilaterally distributed. Alpha and beta power are notably right-lateralized. The NR group, on the other hand, demonstrate a more stable resting network.



Figure 3.  
Power distributions according to frequency band for Resting State. Power (in dB) is represented by colors (dark red = very high, orange = high, yellow = average, light blue = low, dark blue = very low).



## 6. DISCUSSION

The results revealed that the DYS group demonstrated a distinct neurophysiological profile compared to the NR group, wherein the former exhibited an overall larger power activation in the theta and beta frequency bands, as well as a dominance of delta, theta, and beta frequencies across all scalp sites. The NR group presented a more stable resting network characterized by a dominance of alpha frequencies. According to Shephard and colleagues (2018), a resting network marked by frequencies that are either too slow (i.e., delta and theta) or too fast (i.e., beta) would signify an inhibitory/excitatory imbalance and, consequently, a dysfunctional brain network. Alpha frequencies, on the other hand, are correlated with passive attention and are therefore dominant at resting state (Kamel & Saeed Malik, 2015). As the DYS group were observed to have significantly weaker alpha activity, it can be inferred that the DYS group had difficulty in sustaining attention and inhibiting distracting environmental stimuli (Schivone et al., 2014). Comparable results were obtained by Babiloni et al. (2012) and Papagiannopoulou and Lagopoulos (2016).

In the DYS group, increased delta and theta activity was found in the left frontal region, which has been considered to be a critical area in reading development (Richlan, 2012). Abnormalities in the theta band (i.e., overactivation) at resting state have been implicated as a distinct neural signature in dyslexia, suggesting a less integrated network, as well as reduced communication in readers with dyslexia compared to controls. Thus, the observed increase in low frequency activity during eyes-closed resting state in children with dyslexia is a strong indicator of the presence of an atypical network (de Vos et al., 2017; Fraga González et al., 2016; Pagnotta et al., 2015; Papagiannopoulou & Lagopoulos, 2016). Specifically, this resting state atypicality in the left frontal region is manifested by slow and effortful reading as it is correlated with difficulties in phonological processing (Schivone et al., 2014). Moreover, the frontal reading network involves the left inferior frontal gyrus

which plays a key role in speech articulation. Left-hemispheric hypoactivation characterized by an abnormal modulation of delta and theta frequencies is reflective of altered connectivity patterns that have been found to have crucial consequences in processing speech input (van der Mark et al., 2011).

An attenuation of beta frequencies was observed in the left hemisphere as compared to the right hemisphere. The current findings agree with other studies that have reported abnormally stronger beta power in the right hemisphere (de Vos et al., 2017; Dimitriadis et al., 2016, 2018; Jiménez-Bravo et al., 2017; Lizarazu et al., 2015; Power et al., 2016). The beta band is associated with active attention and other activities such as thinking, focusing, and problem solving (Kamel & Saeed Malik, 2015). Thus, beta power activation during resting state can be interpreted as neural hyperactivation. This right-lateralized overexcitability at rest may be attributed to a compensatory mechanism for children with dyslexia (Hoeft et al., 2011; Simos et al., 2011). According to Richlan (2012), right hemisphere compensation in dyslexia increases as phonological demands increase, and that activation in the right hemisphere, whether during reading or at rest, is a mechanism for children with dyslexia to cope with difficulties in visual coding.

These results illustrate that Mobile EEG is an accessible research tool that boasts a capacity to investigate a wider spectrum of research questions for special populations, especially children with dyslexia and other learning disorders, thereby deepening our understanding of neurodevelopmental populations. As we were able to determine differences between normal reading children and children with dyslexia at rest, we are gaining more evidence that mobile EEG can be provide objective assessments of functional brain activity, as well as highly individualized profiles of cognitive functioning.

## **7. LIMITATIONS**

We acknowledge possible limitations of the current study. Firstly, a small sample of children with “pure” dyslexia (i.e., absence of co-morbid conditions) participated in this study. It must be noted that studies involving a highly specific and vulnerable group such as children with dyslexia tend to involve small sample sizes (Franceschini et al., 2013; Franceschini, Bertoni, Gianesini, Gori, & Facoetti 2017; Łuniewska et al., 2018; Ramus, Altarelli, Jednoróg, Zhaod, & Scotto di Covella, 2018), which can potentially weaken the generalizability of the findings. Also, as this study included only male participants, it would be important to also examine resting state EEG involving female children with dyslexia.

## **8. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS**

### **8.1. Conclusions**

In this study, we were able to confirm that dyslexia can be studied using mobile EEG as an assessment tool. This provides evidence that mobile EEG presents a novel opportunity to make brain-based assessments more convenient and available to researchers outside of the laboratory. Analyzing eyes-closed resting state EEG rhythms is essential to better understand the role of abnormal cortical sources in brain-based deficits. The findings of this study confirmed a less integrated language network as evidenced by a dominance of theta activity in the left frontal region at resting state in children with dyslexia. Moreover, atypical alpha and beta activity were also observed. More studies are needed to further explore the neurophysiological characteristics of resting state activity in children with dyslexia.

## 8.2. Future research directions

For our future research, we plan to investigate preliteracy measures of brain function using resting state EEG between children with a family history of dyslexia and those without, which could allow us to uncover the neurophysiological mechanisms of the predisposition to reading difficulties. We will also explore whether reading intervention can affect the neural dynamics of children with dyslexia as revealed by resting state EEG. Future studies should consider using larger and more diverse samples, as well as a wider range of cognitive tasks.

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## KEY TERMS & DEFINITIONS

**Dyslexia:** sometimes called a *reading disability* or *disorder*, it is a type of specific learning disorder characterized by difficulties in reading (Kearns et al., 2019).

**Electroencephalography (EEG):** a typically noninvasive electrophysiological monitoring method used to record electrical activity in the brain by placing electrodes along the scalp (Kamel & Saeed Malik, 2015).

**Mobile EEG:** refers to portable, wireless, wearable, and dry EEG systems (Lau-Zhu et al., 2019).

**EEG frequency bands:** quoted in Hertz (Hz), these refer to EEG rhythms that are defined as delta ( $\delta$ ; 0–4.0 Hz), theta ( $\theta$ ; 4–8 Hz), alpha ( $\alpha$ ; 8–12 Hz), beta ( $\beta$ ; 12–25 Hz), and gamma ( $\gamma$ ; 25–100 Hz).

**EEG power:** values indicating the relative amplitudes of individual EEG bands that reflect the degree of activity of certain brain areas.

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