Visual/Auditory and Orthographic/Phonological Speed of Processing in Colombian Children with Dyslexia and Average Readers: an ERP Study

Velocidad de procesamiento visual / auditivo y ortográfico / fonológico en niños con dislexia y lectores promedio colombianos: un estudio de potenciales relacionados con eventos

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Abstract

This study examined the differences in the speed of processing between the visual-auditory and orthographic-phonological modalities, through the analysis of event-related potentials in children with dyslexia compared with a control group, based on the asynchrony hypothesis of dyslexia. Thirty Spanish-speaking children living in Bogotá, Colombia —15 with developmental dyslexia and 15 average readers paired by age, sex, socio-economic status (SES), and grade—participated in the study. Five behavioral tasks with auditory and visual, linguistic, and non-linguistic stimuli with simultaneous electrophysiological recording were applied to participants in Spanish. There was a significant time difference between the processing of linguistic and non-linguistic visual stimuli, the processing of linguistic and non-linguistic visual vs. auditory stimuli, and the processing

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of words and pseudowords in children with dyslexia compared to average readers. The orthographic and phonological difficulties in dyslexic children are supported by lower P100 amplitudes and deeper N200 deflections to pseudowords, as well as lower P300 amplitudes to both words and pseudowords.
Keywords: developmental dyslexia, event-related potentials, speed of processing, cognitive processes, lexical decision.

Resumen

Este estudio examinó las diferencias en la velocidad de procesamiento entre las modalidades visual-auditiva y ortográfica-fonológica, por medio del análisis de potenciales relacionados con eventos en niños con dislexia comparados con un grupo control, siguiendo la hipótesis causal de la dislexia evolutiva basada en la asincronía en la velocidad de procesamiento. Treinta niños de habla hispana que viven en Bogotá, Colombia —quince con diagnóstico de dislexia evolutiva y quince lectores promedio emparejados por edad, sexo, nivel socioeconómico y grado—, participaron en el estudio. A los participantes se les aplicaron cinco tareas conductuales con estímulos auditivos y visuales, lingüísticos y no lingüísticos con registro electrofisiológico simultáneo. Hubo una diferencia de tiempo significativa entre el procesamiento de estímulos visuales lingüísticos y no lingüísticos, el procesamiento de estímulos visuales versus auditivos lingüísticos y no lingüísticos, y el procesamiento de palabras y seudopalabras en niños con dislexia en comparación con los lectores promedio. Las dificultades ortográficas y fonológicas en los niños disléxicos se evidencian en las amplitudes menores de P100 y las desviaciones más profundas de N200 en seudopalabras, así como en las amplitudes menores de P300, tanto en palabras como en seudopalabras.

Palabras clave: dislexia evolutiva, potenciales relacionados con eventos, velocidad de procesamiento, procesos cognitivos, decisión léxica.

Introduction

Dyslexia is a learning disability with neurobiological background characterized by impaired reading, in which literacy performance is inconsistent with standard intelligence and adequate school instruction in reading (Blomert, 2005; Lyon et al., 2002; Lyon et al., 2003; Snowling, 2013). Neurophysiological studies with visual and auditory EP (evoked potentials) and event-related potentials (ERP's) using orthographic/phonological stimuli have examined wave components in order to identify cognitive processes related to reading processing.

P100 is one of the motion-related visual evoked potentials researched on dyslexia under the hypothesis of magnocellular visual pathway impairment. This component is broader in lateral occipital sites and typically peaks between 100 and 130 ms. P100 early generators are in the dorsal extra striate cortex (middle occipital gyrus) and MT (or V5), and its later generators emerge from the fusiform gyrus. MT is involved in perceiving motion, integrating local motion signals into global percepts, and guiding some eye movements (Born & Bradley, 2005). The P100 latency varies depending on the stimulus contrast, the direction of spatial attention, and the alertness of the subject (Vogel & Luck, 2000). Studies have found mixed results: prolonged latencies (Brecelj et al., 1996; Lehmkuhle et al., 1993) and smaller P100 amplitudes (Mecacci et al., 1983; Solan et al., 1990), suggesting a reduced speed of visual processing and contributing to the hypothesis of a selective weakness of the visual transient system. Other studies have specifically found P100 larger amplitudes and delayed latencies in the right hemisphere of dyslexic participants (Kang et al., 2016).

N200 is a negative event-related potential typically occurring at approximately 200 ms after stimulus onset, characterized by a frontal-central scalp distribution. This component is larger for uncommon targets. Both auditory and visual deviants will, if task-relevant, elicit an N200 component, with a largest effect over central sites for auditory stimuli and over posterior sites for visual stimuli (Simson et al., 1977). This component has also been found to appear in skilled readers, in the visual word form area at the left hemisphere, around 285 ms after presentation of words.

N200 has been associated with sustained attention, classification, and discrimination of stimuli (Luck, 2005), although it can be generated in situations that do not demand attention (Shaul, 2008). Its amplitude increases with the task difficulty and in response to infrequent stimuli. Their latencies are shorter during tasks that involve sustained attention than during those that require divided attention. The latencies are also shorter after the presentation of infrequent stimuli, compared to standard stimuli. N200 has been identified as the first target detection index (Shaul, 2008). In word paradigms research, it has been reported to be generated by physically unexpected stimuli. Research on visual spatial attention and letter detection has suggested that N200 may reflect an early, partially automatic process of matching with a template (Wijers et al., 1997).

Regarding this ERP, researchers have found delayed N200 latencies among dyslexics in response to both linguistic and nonlinguistic stimuli (Fawcett et al., 1993; Neville et al., 1993; Taylor & Keenan, 1990; Taylor & Keenan, 1999).

In a tone categorization task applied by Vila and Barbero (2000), the dyslexic children showed maximum longer N200 latencies in the Left Temporal-Parietal region and bilateral in the Occipital region compared to average readers.

An even later and more studied component is P300, a late positive ERP, with its onset around 300 ms after the presentation of a stimulus. It is related to context updating (Donchin, 1981), working memory, and decision making (Donchin & Isreal, 1980). It is reliably evoked during tasks that require stimuli discrimination, such as the auditory oddball paradigm. The P300 amplitude has been suggested to reflect task relevance (Hillyard & Picton, 1978) and probability (Duncan-Johnson & Donchin, 1982), whereas the P300 latency indexes the timing of higher-order cognitive processes as well as the speed of processing (Polich, 1987). P300 does not require a verbal response. Therefore, it has been shown to be an effective tool in the objective evaluation of reading alterations (Mendonça et al., 2013).

Significant differences have been found between linguistic and non-linguistic stimuli processing, among children with dyslexia and average readers on this component. For example, symbols have generated P300 waves of greater amplitude and longer latencies than words in dyslexic readers (Holcomb et al., 1986). Smaller P300 amplitudes have been found for lexical stimuli compared to non-lexical visual stimuli (characters) among children with dyslexia (Barnea et al., 1994).

There is evidence of shorter latencies found in P300 wave among children with dyslexia in response to linguistic auditory stimuli (Merzenich et al., 1996; Tallal, 1993) and to non-linguistic auditory stimuli (Holcomb et al., 1986; Lovrich & Stamm 1983; Maciejewska et al., 2013). Other researchers have found different patterns: smaller amplitudes and longer latencies of P300 in response to verbal stimuli compared to non-verbal stimuli (Erez & Pratt, 1992), longer P300 latencies without differences in the P300 amplitudes (Fawcett et al., 1993; Maciejewska, et al., 2013), or no significant between-group differences in P300 amplitude and latency (Oliveira et al., 2013).

Some of the works most focused on the comparison of visual and auditory, linguistic and non-linguistic stimuli were those of Breznitz (2002, 2003), who tested whether there was a temporal gap between the speed of processing (SOP) of the visual-orthographic and auditory-phonological modalities in children with dyslexia, caused by a failure in stimuli integration, which consequently affects word recognition. In her 2002 study, Breznitz found that dyslexic children in primary school were significantly slower than normal readers, matched by chronological age in most of the experimental tasks with a systematic interval of SOP in P200 and P300 components between the auditory-phonological and visual-orthographic modalities. These findings led Breznitz to argue that asynchrony between rates of processing of auditory and visual modalities could be an underlying cause of dyslexia.

Based on Breznitz studies, we aimed to research the differences between the SOP of the visual-orthographic and auditory-phonological modalities in children with dyslexia and average readers, by means of EEG's recorded during visual and auditory tasks with linguistic and non-linguistic stimuli.

Materials and Methods

Participants

The sample (*N* = 30) consisted of a group of 15 participants with a diagnosis of reading disorder[6] and 15 participants as part of the control group, matched by age (between 7 and 12 years), sex, grade (between 1° and 6°), and socioeconomic status (SES: 2nd-6th level).

For the dyslexic group the following were the inclusion criteria: 1) schooling between 1st and 6th grade, 2) normal to corrected vision and hearing, 3) voluntary entry to the study with prior informed consent, and 4) diagnosis of reading disorder (315.00, DSM-IV), mainly characterized by a reading achievement (i.e., reading accuracy, speed, or comprehension as measured by an individually administered standardized test) that falls substantially below what expected, given the individual's chronological age, measured intelligence, and age-appropriate education (Criterion A; APA, 2002)7. Considering the

[6] From here on we will use the term developmental dyslexia as a synonym.

[7] Criterion A was the most relevant to diagnose children with reading disorder in a standardized way. Criterion B, which comments on the interference with academic achievement or with activities of daily living that require reading skills, was met through the reports from parents of the children while filling in the medical record. Participants with a sensory deficit were excluded; therefore, Criterion C of DSM-IV was not relevant for diagnosis.

variety of definitions and lack of consensus on the characteristics of dyslexia in Spanish, we decided to follow the diagnosis criteria of DSM-IV.

The following were the exclusion criteria: 1) left-hand preference[8]; 2) IQ < 85, sensory type (auditory, visual) or neurological deficits, brain injuries, autism, or pervasive developmental disorder; 3) medication affecting the central nervous system; 4) non-formal education or lack of schooling; and 5) students below 1st grade or above 7th grade.

For the control group, the following were the inclusion criteria: 1) schooling between 1st and 6th grade, 2) normal to corrected vision and hearing, 3) voluntary entry to study with prior informed consent, and 4) average academic performance according to academic grades (> 70%).

The following were the exclusion criteria: 1) left-hand preference; 2) sensory type deficits (auditory, visual), neurological deficits, brain injuries, autism, or pervasive developmental disorder; 3) use of medication affecting central nervous system; 4) non-formal education, or lack of schooling; 5) students below 1st grade or above 7th grade; 6) diagnosis of reading disorder (DSM-IV); and 7) behavioral difficulties reported in the Child Neuropsychological Assessment parents' questionnaire.

Data Collection Instruments

Neuropsychological Assessment to Establish Dyslexia Diagnosis

The research employed "Evaluación Neuropsicológica Infantil" [Child Neuropsychological Assessment; Matute et al., 2007], designed for Spanish speaking children, in order to detect cognitive and behavioral changes. This assessment was appropriate for research participants because of its age range (from 5 years 0 months to 16 years 11 months), and because it was previously standardized with Colombian and Latin American population (Matute et al., 2014). Memory, auditory perception, reading, writing, and metalinguistic skills subtests were applied to the sample because of their influence over reading performance. Items were administered in a single session of approximately two and a half hours, but it took longer for participants with signs of developmental dyslexia.

[8] To avoid potential biases related to hemispheric dominance and language specialization.

We also applied letter identification name or letter sounds, equal-different and lexical processing items test (words reading, pseudowords reading) from PROLEC-R, a battery for reading assessment in primary school children (Cuetos et al., 2014).

The Wechsler Intelligence Scale for Children, IV version (WISC-IV; Wechsler, 2003), was administered only to children with signs of dyslexia, to detect a discrepancy between the average IQ (> 85) and reading underachievement (ENI and PROLEC-R tests results), in order to meet the diagnostic criterion *A* of DSM-IV (APA, 2002). Examiners administered the WISC IV battery in a single four-hour session with a break of half an hour, or in two-hour sessions.

Behavioral Tasks

Experimental Design. Participants were presented with five behavioral tasks designed on E-Prime 3.0 software (Psychology Software Tools, 2016) with simultaneous EEG recording. Table 1 presents stimuli shown to participants on the different tasks.

Table 1

Stimuli shown to the participants on each task

Type of task	Name of task	Stimulus 1 (infrequent)	Stimulus 2 (frequent)
Low-level auditory linguistic processing	Bada	ba syllable sound	da syllable sound
High-level orthographic- phonological processing	Lexical Decision	Word	Pseudoword
Low-level visual linguistic processing	Visual Decision	q	p
Low-level auditory non-linguistic processing	HERTZ	Low tone (500 Hz)	High tone (1500 Hz)
Low-level visual non-linguistic processing	IMAGE	Similar-to-mirrored-L-image	Similar-to-inverted-T-image

Source: Own work. Tasks were based on Breznitz (2002, 2003), Breznitz and Meyler (2003), Breznitz and Misra, (2003), and Miller-Shaul and Breznitz (2004).

All tasks followed the frequency of the stimuli using *oddball paradigm*: a type of task to assess selective attention, in which participants are asked to respond to a rare and relevant stimulus and ignore a frequent and irrelevant stimulus, but in this research children were always asked to respond to all stimuli presented. An appearance frequency proportion of 30% of the infrequent stimulus (stimulus 1) versus 70% of the frequent stimulus (stimulus 2) was programmed, except for the Lexical Decision task, in which the proportion ratio was 50% / 50%, given the stimuli complexity.

On the Bada, Hertz, Image and Visual Decision Task, a cross fixation mask was presented on the computer screen with a duration of 300 ms. Then, there was an interval of 300 ms. Finally, each stimulus was presented with a duration of 1200 ms. Each complete trial of these tasks (mask+interval+stimulus presentation) lasted 1800 ms.

On the Lexical Decision task, the four asterisks mask lasted 400 ms, followed by an interval of another 400 ms and a stimulus presentation that lasted 1600 ms. Each complete trial of the Lexical Decision task (mask+interval+stimulus presentation) lasted 2400 ms.

For all tasks, children answered to the stimuli during the time of their presentation.

Procedure

Instructions for each task appeared on the computer screen. The main researcher read them aloud while participants were shown a sheet with stimuli instructions. Participants were told to answer as quickly and as accurately as they could, by pressing one of two keys with the index finger of each hand: one with a yellow sticker, assigned to the frequent stimulus; the other, with a green sticker, assigned to the infrequent stimulus. Key stickers were counterbalanced. Participants were asked to repeat aloud instructions to confirm their understanding. Twelve randomized training items were presented on each task. The researcher showed the sheet with instructions for a second time to avoid participant's doubts.

100 stimuli per task were presented to each participant on the screen of a Samsung monitor 21" (1280 x 800 pi) with a refresh rate of 60 Hz and a

70 cm distance from the eyes. On auditory processing tasks, stimuli were presented through speakers located equidistantly to the participant. All tasks administration was conducted in one session at the Laboratory of Experimental Psychology at El Bosque University, with an approximate length of 120 minutes (including prior placement of the cap with electrodes, the execution of five tasks, plus breaks between each task). The order of stimuli presentation was counterbalanced.

Electrophysiological Recording

During the administration of the tasks in the laboratory, external sounds were dimmed and there was adequate lighting. BrainVision Recorder software (amplifier BrainAmp, A / D converter 16-bit) registered electroencephalographic (EEG) activity of Ag/Ag Cl electrodes in 32 channels Fp2, F3, F4, C3, C4, FC1, FC2, FC6, CP1, CP2, CP5, CP6, P3, P4, PO9, PO10, O1, O2, T7, T8, TP9, TP10, Fz, Cz, Pz, Oz.

The electrooculogram (EOG) was recorded in outer cantus (FC5), left eye's infraocular orbit (F7) and supraocular orbit (Fp1), and in the outer cantus (F8) of the right eye. The electrode assembly was done according to the International 10/20 system in a nylon cap (actiCAP, Brain Products).

By using actiCAP software, the electrode impedances were controlled below 5 kΩ. Prior preparation of electrooculogram, scalp recording areas were applied with abrasive gel. Then, the electrolytic gel was applied to all electrodes. The following parameters for recording signals were established with the Brain Vision Recorder: Sampling rate = 500 Hz, Low cutoff = 0.05 Hz, High cutoff = 40 Hz, Notch filter = 60 Hz (constant time of 3.1831 s).

We collected data in epochs of 300 ms (pre-stimulus) to 800 ms (post-stimulus) (length = 1100 ms) for all the recording channels, after the presentation of the training items. Stimuli length was determined to allow the participants time to observe and respond. This would have not been possible with shorter times; on the other hand, longer times would have lengthened the execution of the tasks by the participants without implying they might have a better performance. Researchers asked participants to avoid eye and sudden facial movements to reduce artifacts. Recorded data was stored off-line for cleaning, averaging, and further analysis.

Filters were applied to the raw records (Low cutoff = 0.1 Hz; High cutoff = 30 Hz; slope (dB / oct) = 12), in order to remove as many artifacts as possible. Ocular correction was performed (vertical = Fp1, F7; horizontal = F8, FC5). Then, global segmentation was done (Range = -200 - 800 ms) according to stimuli for each task. Baseline correction was implemented (Range = -100 - 0 ms) and artifacts were rejected based on visual inspection (Minimum allowed activity = 0.5 µV; Interval = 100 ms). Segmentation of stimuli was defined on each individual record (Range = -200 and 800 ms).

Averaging and Peak Detection

We obtained the average of stimuli 1 and 2 separately and the grand average for each task and stimulus. In order to obtain a parameter for detecting individual peaks, researchers performed peak detection of grand averages. Then, considering the latency of the highest voltage peak of each component (in most tasks was that of the Oz channel and therefore it was taken as a benchmark), analysis windows for automatic detection of individual peaks of components for each task were determined (see Appendix 1).

Statistical Analysis

The main aim of the statistical analysis was to find whether there were differences between the speed of processing (SOP) of the visual-orthographic and auditory-phonological modalities, by means of visual and auditory evoked potentials and event-related potentials, in children with dyslexia and average readers. To accomplish this aim, we conducted Mann Whitneys' U independent samples analysis between both groups per peak, stimulus, and task.

We ran intra-group Wilcoxon's Signed Rank Test for related samples between tasks of the same modality (visual or auditory) and between visual and auditory tasks, in order to better understand the extent of difference between stimuli processing of both dyslexic and average readers. Differences between latencies of the same wave (P100-P100; N200-N200; P300-P300) across the same-modality tasks (Visual modality = Visual Decision task - Image task; Auditory modality = Bada task - Hertz task) were also obtained.

A further aim was to analyze cross-modality gap scores to find differences in speed of processing between modalities. To address it, we subtracted the latencies between contiguous peaks (P300-N200; N200-P100) and we ran Mann Whitneys' U independent samples analysis between both groups.

Non-parametric Mann-Whitney's U test for independent samples and Wilcoxon's Signed Rank Test for related samples were used, because of their suitability for small data sets, in which normality cannot be assumed due to the sampling size. SPSS statistical software was used for data analysis. Data concerning both descriptive statistics and non-parametric inferential statistics will be illustrated in tables.

Results and Discussion

Behavioral measures

Neuropsychological Tests

Individuals with dyslexia showed significantly worst performance than the control group on these ENI battery's tasks: Naming, Spelling, Syllables Reading, Sentences Reading, Sentences Comprehension, Number of Incorrectly Read Aloud Words (ENI), Words Read Aloud per Minute (Speed), Silently Read Words per Minute (Speed), Words Copy, Time in a Text Copy, Number of Words Copied per Minute, and PROLEC's Words Reading and Pseudowords Reading, as seen on Appendix 2.

We found the worst performance on individuals with dyslexia on tasks specifically related to phonological abilities (Naming, Spelling). These results are aligned with those of other investigations, indicating that most children with dyslexia have significant difficulty learning to map alphabetic symbols to sound and acquiring facility in phonological decoding (letter-sound) and subsequently in phonological awareness (Breznitz, 2002; Fletcher et al., 1994; Liberman & Shankweiler, 1979, 1991; Snowling, 1980, 2000; Stanovich & Siegel, 1994; Torgesen et al., 1999; Torgesen et al., 2001; Vellutino, 1979;

Vellutino et al., 1994, 1995, 1996; Wagner & Torgesen, 1987; Wagner et al., 1994). Our dyslexic participants also exhibited the worst performance in overall reading abilities (Syllables Reading, Words Reading, Pseudowords Reading, Sentences Reading, Sentences Comprehension), timing measures (Number of Incorrectly Read Aloud Words, Words Read Aloud per Minute, Silently Read Words per Minute), which was similar to findings reported by Breznitz (2002), and writing abilities (Words Copy, Time in a Text Copy, Number of Words Copied per Minute).

Reaction Times

As seen on Table 2, a significant difference was found ($p < 0.01$) between the medians of RT's of control and dyslexic group in both stimuli of Hertz task (low and high tone, non-linguistic, low level auditory task), and Image task (similar -to-mirrored L- image and similar-to-inverted T-image, non-linguistic, low level visual task), as well as a significant difference ($p < 0.05$) in the reaction times to words in the Lexical Decision task (linguistic, high level orthographic-phonological task). To all these stimuli, means and medians of RT's of dyslexic children were longer than those of the control group. This outcome resembles that of Breznitz (2002), who found reaction times were significantly longer among dyslexic than normal readers in all of the low- and high-level tasks (Miller-Shaul & Breznitz, 2004), although the current research did not find longer reaction times among dyslexic children in other low level processing tasks such as Bada and Visual Decision task.

Table 2
Reaction Times (ms)

Task	Control			Dyslexic					
	Mdn	*Mean*	*SD*	*Mdn*	*Mean*	*SD*	*U*	*Z*	*p-value*
Bada (ba)	732.000	714.895	222.435	742.000	727.366	214.701	84550.5	-0.805	0.421
Bada (da)	636.500	659.980	215.128	669.000	677.224	206.679	452344.0	-1.960	0.050
Lexical Decision (words)	846.000	893.033	251.317	920.500	924.432	338.850	203021.5	-2.414	0.016*
Lexical Decision (pseudowords)	1004.000	1025.371	269.378	1017.000	994.182	358.473	169685.5	-0.757	0.449

Visual Decision (q)	579.000	587.276	173.045	572.000	584.358	201.314	91474.0	-0.559	0.576
Visual Decision (p)	519.000	553.245	183.786	523.000	545.349	189.147	497018.0	-0.499	0.618
HERTZ (low tone)	500.000	523.166	206.317	570.000	571.885	191.162	72829.5	-4.825	0.000**
HERTZ (high tone)	470.000	505.140	207.129	519.500	538.530	190.763	407197.5	-5.370	0.000**
IMAGE (similar-to-mirrored L-image)	490.500	532.320	184.366	554.000	569.793	182.289	429566.5	-6.575	0.000**
IMAGE (similar-to-inverted T-image)	537.000	560.778	177.099	571.500	588.694	175.752	84764.0	-3.244	0.001**

Note. Mdn = Median; *SD* = Standard Deviation; *U* = Mann-Whitney U score, *Z* = Z score, $^{*}p < 0.05$, $^{**}p < 0.01$.

Accuracy

Significant differences were found in the accuracy of both Lexical Decision task stimuli (Words and Pseudowords = $p < 0.01$) and Visual Decision task stimuli (*q* letter = $p < 0.01$; p letter = $p < 0.05$, linguistic, low level visual task). In both stimuli of these two tasks, the accuracy means and medians of dyslexic group were lower than those of the control group (see Table 3). This finding is comparable to that of Breznitz (2002), who found dyslexic readers obtained significantly lower scores than the control group in a low level visual linguistic task. She also found children with dyslexia with significantly lower accuracy in auditory non-linguistic and auditory linguistic tasks; conversely, we did not obtain these results in our research.

In addition, at the higher processing level tasks, Breznitz (2002), as well as Miller-Shaul and Breznitz (2004), also reported significantly lower scores in all measures for children with dyslexia. Our research also reported lower accuracy for words and pseudowords in the case group on the Lexical Decision task (high level task).

Table 3
Accuracy (ratio)

Task	Control			Dyslexic					
	Mdn	*Mean*	*SD*	*Mdn*	*Mean*	*SD*	*U*	*Z*	*p-value*
Bada (ba)	0.867	0.762	0.248	0.800	0.700	0.197	73.000	-1.652	0.098
Bada (da)	0.900	0.803	0.212	0.814	0.760	0.238	92.000	-0.852	0.394
Lexical Decision (words)	0.920	0.897	0.073	0.750	0.775	0.100	37.500	-3.117	0.002**
Lexical Decision (pseudowords)	0.860	0.809	0.193	0.450	0.529	0.227	37.000	-3.134	0.002**
Visual Decision (q)	0.930	0.903	0.085	0.750	0.639	0.305	33.500	-3.291	0.001**
Visual Decision (p)	0.970	0.946	0.047	0.910	0.735	0.352	61.500	-2.129	0.033*
HERTZ (low tone)	0.897	0.848	0.167	0.862	0.816	0.169	98.000	-0.602	0.547
HERTZ (high tone)	0.970	0.929	0.095	0.956	0.902	0.186	102.500	-0.415	0.678
IMAGE (similar-to-mirrored L)	1.000	0.960	0.063	0.900	0.913	0.092	79.000	-1.543	0.123
IMAGE (similar-to-inverted T)	0.900	0.927	0.070	0.900	0.853	0.136	78.500	-1.491	0.136

Note. *Mdn* = Median; *SD* = Standard Deviation; *U* = Mann-Whitney U score, *Z* = Z score, $*p < 0.05$, $**p < 0.01$. Accuracy is measured as a ratio between the number of accurate and inaccurate attempts. The range varies between 0 (no accuracy) and 1 (accuracy).

Electrophysiological Measures

Through visual inspection of grand average waves and the definition of analysis windows for Grand Average Peak Detection and automatic detection of individual peaks, we recognized three peaks on Lexical Decision task, Visual Decision task, Image and Hertz tasks: a prominent positive peak approximately between 100 and 200 ms (P100); a deep negative deflection reaching maximum amplitude between 150 and 200 ms (N200); and a positive peak, between 300 and 400 ms, approximately (P300). In Bada task, researchers identified two positive late peaks: one at 500 ms and another one at 700 ms. These late latencies peaks were distinguished as P300 and P600, respectively.

We selected the following electrodes considering their highest latencies and amplitude values at each wave peak: Oz and Pz channels (Central Occipital and Parietal) in all tasks, PO9 and PO10 (Parietal-Occipital) for the analysis of P100 component; TP9 and TP10 (Temporal-Parietal) for N200; P7 and P8 (Parietal) for P300 analysis.

Comparison between groups per channel, per stimulus and per task

Most differences between dyslexic and control group occurred in the Lexical Decision task. The differences between groups are summarized by wave peak and are detailed on Appendix 3.

P100. In the Lexical Decision task, the P100 amplitude of children with dyslexia was significantly lower at Parietal-Occipital channels (PO9 and PO10) to pseudowords ($p < 0.05$) compared to the control group.

In the Visual Decision task, only the P100 wave peak reported a significantly lower amplitude for dyslexic readers compared to average readers in the Oz channel ($p < 0.05$) when the q letter was shown on the screen.

This smaller amplitude of P100 visual evoked potentials has been also reported in other investigations (Mecacci et al., 1983; Solan et al., 1990), suggesting a reduced speed of visual processing, related to a selective weakness of the visual transient system in children with reading disabilities.

In addition, in P100 wave peak of the Hertz task the latency was significantly longer for dyslexic children than for skilled readers when the high tone (PO9 = $p < 0.05$) and the low tone were presented (PO10 = $p < 0.01$). As the P100 latency varies depending on the alertness of the subject (Vogel & Luck, 2000), this variable has possibly influenced a different outcome for children with dyslexia, who have been found to have attentional difficulties (Lewandowska et al., 2014).

N200. In the Lexical Decision task, participants with dyslexia exhibited deeper deflections than the control group to both words (TP9 = $p < 0.05$; TP10 = $p < 0.01$) and pseudowords (TP9 and TP10 = $p < 0.01$). Research on visual spatial attention and letter detection has suggested that N200 may reflect an early, partially automatic process of matching with a template (Wijers et al., 1997). Therefore, children with dyslexia required more cognitive resources than average readers, especially when decoding the letters of both words and pseudowords to match them to their stored mental representations. This decoding and mapping of sounds to letters was more demanding for children with dyslexia as their phonological awareness is affected (Caravolas, 2005). In addition, these larger responses on N200 reflects a maturational delay (Kuuluvainen et al., 2016).

In the Hertz task, significant differences ($p < 0.05$) were also found in the amplitude of the wave, as the control group showed a greater negative deflection to high tone compared to dyslexic children (TP10 = $p < 0.05$). The frequent stimulus required a more detailed processing than the infrequent stimulus for the control group. The small size of the negative deflection in children with dyslexia could reveal a deficit in stimulus categorization not restricted to linguistic stimuli, which could affect the development of basic reading skills (Vila & Barbero, 2000).

P300. The amplitude was significantly lower for dyslexic children compared to average readers when they were presented with words and pseudowords (P7 = $p < 0.05$) during the Lexical Decision task. These results are opposite to those of Miller-Shaul and Breznitz (2004), who found higher amplitudes among dyslexic readers compared to typical readers.

Intramodal latencies comparison between linguistic and non-linguistic stimuli tasks

Intragroup Wilcoxon's Signed Rank Tests between tasks of the same modality (visual or auditory) were run to understand the extent of difference in the speed of stimuli processing for both groups.

Bada and Hertz tasks (Auditory Intramodal) comparison. Significantly longer P300 median latencies ($p < 0.01$) were obtained to Bada task stimuli compared to Hertz task stimuli in both groups at P7, P8, Oz, and Pz. Non-linguistic stimuli were easier to process for average readers, as well as for children with dyslexia, considering that P300 latencies indexes the timing of higher-order cognitive processes as well as the speed of processing (Polich, 1987).

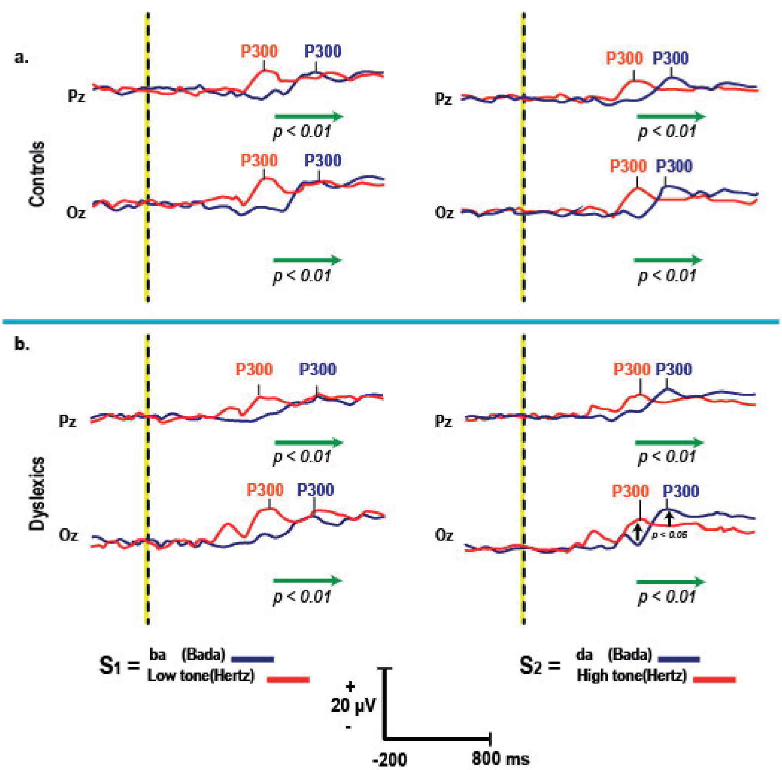
In the dyslexic group, a significantly higher amplitude was found to the frequent stimulus of Bada task (da syllable) compared to that of Hertz task (high tone), at P7 (Bada's *Mdn* = 14.636, Hertz' *Mdn* = 10.585, $z = -2.329^{c}$[9], $p < 0.05$), P8 (Bada's *Mdn* = 12.923, Hertz's *Mdn* = 9.067, $z = -3.067^{c}$, $p < 0.01$), and Oz (Bada's *Mdn* = 12.479, Hertz' *Mdn* = 11.009, $z = -2.158^{c}$, $p < 0.05$; see Figure 1). Control group did not show these significant dif-

[9] ^{C} = it is based on negative ranks.

ferences regarding the amplitude of P300 to the frequent stimulus of Bada and Hertz tasks at P8 and Oz. As the P300 amplitude has been suggested to reflect probability, or expectancy of the eliciting stimulus (Comerchero & Polich, 1999), we can say that children with dyslexia considered frequent stimuli more probable than infrequent stimuli within this task. Although there is no relevant literature supporting this finding, we consider it was important to explain it in accordance with the probability or expectancy of stimuli for dyslexic children.

Figure 1

Intramodal comparison between auditory tasks. Bada and Hertz tasks - P300. a. Controls, b. Dyslexics. Horizontal arrows = latency (ms), vertical arrows = amplitude (µV). Positive polarity upwards. Graphics from BrainVision Analyzer software



Visual Decision task and Image task (Visual Intramodal) comparison

P100. Significantly longer P100 latencies to Visual Decision task stimuli compared to those of Image task were found for both groups, an expected result following Breznitz' results (2002), as the processing of linguistic stimuli is thought to be more complex than that of non-linguistic stimuli.

Nevertheless, latencies were longer to both stimuli (frequent and infrequent) in the control group whereas only to the frequent stimulus in the group with dyslexia: control group showed significant longer median latencies ($p < 0.05$) to the infrequent stimulus of the Visual Decision task (q letter) at Oz and Pz ($p < 0.05$) compared to the infrequent stimulus of the Image task (similar-to-mirrored-L). Longer latencies were also found to the frequent stimulus of the Visual Decision task at PO9 and Oz channels ($p < 0.01$). A significantly longer latency ($p < 0.05$) was also found only to p letter, in comparison with similar-to-inverted T-image at PO9 and Oz, in dyslexic children compared to average readers (see Appendix 4). Exogenous factors (luminance, spatial attention, etc.) may have affected attention to each stimulus on each group (Johannes et al., 1995).

A significantly higher amplitude ($p < 0.05$) was also found to q letter in comparison with similar-to-mirrored L (infrequent stimuli) for control group at PO9 and Oz; whereas in children with dyslexia, the amplitude difference was only significant for the p letter (frequent stimulus) at the Oz channel. This difference can be possibly related to the place of the generating focus of the wave (Luck, 2005).

N200. Only the control group had longer latencies to the frequent stimulus of Visual Decision task at TP10 (Right Temporal Parietal electrode; p letter, $Mdn = 234$ vs. similar-to-inverted T-image, $Mdn = 232$, $z = -2.932^c$, $p < 0.01$) and to the infrequent stimulus at Pz (Central Parietal site; q letter, $Mdn = 236$ vs. similar-to-mirrored L, $Mdn = 222$, $z = -2.131^c$, $p < 0.05$). The reason behind these findings might be that for children with dyslexia the speed of processing of these visual stimuli (letters and images) is not different, while for average readers, the processing of letters is more detailed than the processing of images. The processing of linguistic stimuli is thought to be more complex than that of non-linguistic stimuli. Therefore, it takes longer as it requires to analyze and to categorize them (Luck, 2005).

Nevertheless, shorter latencies (z = -2.305[d][10], $p < 0.05$) to p letter (*Mdn* = 222) compared to similar-to-inverted T-image stimulus (*Mdn* = 234) were also found at Pz only for the control group, meaning that average readers did not have to put great effort into the decision making between frequent and infrequent stimulus (Donchin & Isreal, 1980).

P300. A significantly longer latency ($p < 0.05$) was found to Image task stimuli compared to Visual Decision task stimuli in both groups, but to a different stimulus: to the infrequent stimulus in the group with dyslexia (similar-to-mirrored L-image, Pz's *Mdn* = 364; q letter, Pz's *Mdn* = 330, z = -2.216[c]), and to the frequent stimulus in the group of average readers (similar-to-inverted T-image, Pz's *Mdn* = 358; p letter, Pz's *Mdn* = 334, z = -2.261[c]). In accordance with literature, children with dyslexia devoted more time to the processing of infrequent stimuli, the kind of stimulus that generates event-related potentials (Polich, 1987).

Intermodal (visual-auditory) comparison between non-linguistic stimuli tasks

Intra-group Wilcoxon's Signed Rank Tests between visual and auditory tasks were applied in order to better understand the differences between the processing of visual and auditory stimuli of both dyslexic and average readers.

Image and Hertz tasks

P100. The latency was significantly longer ($p < 0.01$) at Parietal-Central (Pz), Parietal-Occipital sites (PO9, PO10), and Central-Occipital site (Oz) for Hertz task's stimuli compared to Image task in both groups.

Significantly greater amplitudes of Image stimuli compared to Hertz stimuli were reported for both groups as described by Polich and Heine (1996). Nevertheless, the highest amplitudes were reported from different channels for children with dyslexia and average readers. For example, significantly greater

[10] [d] = it is based on positive ranks.

amplitudes of Image stimuli ($p < 0.01$) were obtained at PO10 (similar-to-inverted T-image, frequent stimulus, *Mdn* = 11.884), Oz (similar-to-mirrored L-image, infrequent stimulus, *Mdn* = 11.583; similar-to-inverted T, frequent stimulus, *Mdn* = 15.112), and Pz (similar-to-inverted T-image, frequent stimulus, *Mdn* = 3.253), compared to Hertz stimuli (high tone, frequent stimulus, PO10's *Mdn* = 0.199, $z = -2.272^{d}$; low tone, infrequent stimulus, Oz's *Mdn* = 2.335, $z = -2.783^{d}$; high tone, frequent stimulus, Oz's *Mdn* = 1.859, $z = -3.237^{d}$; high tone Pz's *Mdn* = 0.608, $z = -2.158^{d}$) in the control group. The dyslexic group only presented significantly higher amplitudes at PO9 (*Mdn* = 8.213, $z = -2.045^{d}$, $p < 0.05$) and at Oz (*Mdn* = 10.431, $z = -2.329^{d}$, $p < 0.05$) to similar-to-inverted T-image (frequent stimulus), compared to high tone (PO9's *Mdn* = -3226 and Oz's *Mdn* = 3571). Differences observed in the topographic distribution of voltages between both groups of children can be associated with task variations that may influence the processing of low-level auditory and visual stimuli. Also, because the auditory P1 component bears no particular relationship to the visual P1 component (Luck, 2005).

N200. Significantly delayed latencies were found at Temporal-Parietal sites (TP9, TP10), Occipital-Central (Oz), and Parietal-Central (Pz) to the high and low tone of Hertz task in both groups ($p < 0.01$), compared to the visual stimuli of Image task, which means that the processing of low-level auditory stimuli took longer than the processing of low-level visual stimuli (Breznitz, 2002).

Greater negative deflections appeared to both stimuli of Image compared to the stimuli of Hertz task in both groups. In the control group, the negative deflection was significantly greater for both stimuli of Image (similar-to-mirrored L-image, *Mdn* = -14.348; similar-to-inverted-T image, *Mdn* = -15.459) than for Hertz task stimuli (low tone, *Mdn* = -6.926; high tone, *Mdn* = -6.728) at Oz ($z = -3.010^{c}$, $z = -2.783^{c}$, respectively, $p < 0.01$) and at Pz, (similar-to-mirrored L-image, *Mdn* = -6.514; low tone, *Mdn* = -3.680, $z = -2.442^{c}$, $p < 0.05$; similar-to-inverted T-image stimulus, *Mdn* = -6.964, compared to high tone, *Mdn* = -3.286, $z = -2.783^{c}$, $p < 0.01$). The same pattern occurred in the dyslexic group: significantly greater amplitude to Image stimuli compared to Hertz task's stimuli in all electrodes ($p < 0.01$, z = [(-3.408^{c}) - (-2.613^{c})].

This finding informs us that possibly both groups had a more detailed classification and differentiation of non-linguistic visual stimuli than of non-linguistic auditory stimuli (Breznitz, 2002).

P300. Latency was longer on Hertz task than on Image task stimuli in both groups at Parietal (P7, P8), Central-Occipital (Oz), and Central-Parietal (Pz) sites ($p < 0.01$). For the control group, the amplitude was significantly higher ($z = -2.101^c$, $p < 0.05$) only at P8, on the Hertz task, when the high tone (frequent stimulus, *Mdn* = 11.126) was compared to similar-to-inverted T-image (frequent stimulus, *Mdn* = 7.575). While in the dyslexic group, significantly greater amplitude on Hertz was found ($z = -2.045^c$, $p < 0.05$) only at P7 to low tone (infrequent stimulus, *Mdn* = 9.813), when compared to similar-to-mirrored L-image (infrequent stimulus, *Mdn* = 5.643). Despite the topographic localization of these differences in amplitude, we cannot dare to establish differentiated stimuli cognitive processing zones in children with dyslexia and average readers, considering that the generating foci of the event-related potentials can vary and that they are the result of a grand average of the wave peaks found (Luck, 2005).

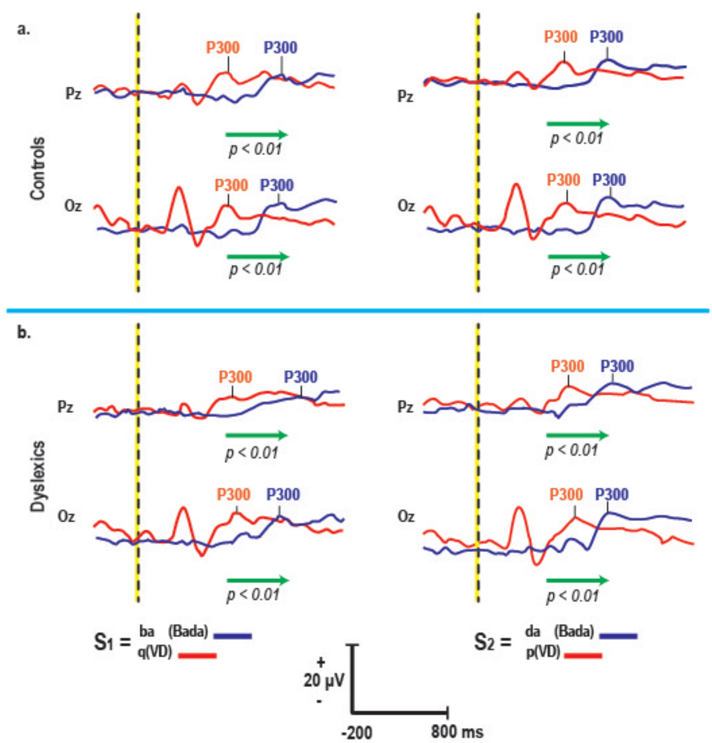
Intermodal comparison (visual-auditory) between linguistic stimuli tasks

Visual Decision and Bada tasks. As seen on Figure 2, significantly prolonged P300 latencies (ms) were found in control group to Bada stimuli compared to Visual Decision task stimuli ($p < 0.01$) at P7, P8, Oz, and Pz. The same was true for the dyslexic group. The processing of auditory linguistic stimuli was more complex and delayed than the processing of visual linguistic stimuli for both groups, disregarding the reading abilities of children. As opposed to visual stimuli, auditory stimuli requires the participant to hear at least part of the sound before starting to process it. A very different finding from Breznitz (2002) research, as she found the largest differences for P300 latency gaps on the sound alike-look alike measure and in the linguistic/auditory-linguistic/visual measures of children with dyslexia. An opposite finding, as well, to that of Polich and Heine (1996), who described the P300 as shorter in latency in response to auditory as opposed to visual stimuli.

The only significant difference regarding amplitudes occurred at P7 to the infrequent stimulus (ba syllable *Mdn* = 14138, q letter *Mdn* = 10.924, $z = -2.329^{c}$, $p < 0.05$) in the control group, while to the frequent stimulus (da syllable *Mdn* = 14636, p letter *Mdn* = 6.013, $z = -2.045^{c}$, $p < 0.05$) in the group with dyslexia. This finding can be explained following Kramer et al. work (1991), in which they found P300 as being related to cognitive resource allocation and task involvement. Possibly typical readers focused more on the infrequent stimulus, while the dyslexic children focused more on the frequent stimulus.

Figure 2

Intramodal comparison between linguistic tasks. Visual Decision task and Bada task - P300. A. Controls b. Dyslexics. Horizontal arrows signposts latency. Source: Graphics obtained from BrainVision Analyzer software



Differences between wave peak latencies

Intramodal e Intermodal Differences in Latencies. Differences between latencies of the same wave (P100-P100; N200-N200; P300-P300) across same-modality tasks with different stimuli (Visual modality: Visual Decision task [linguistic stimuli] - Image task [non-linguistic stimuli]; Auditory modality: Bada task [linguistic stimuli] - Hertz task [non-linguistic stimuli]) were obtained. These values accounted for specific speed of processing of visual and auditory modalities in children with dyslexia compared to average readers.

The Mann-Whitney test applied produced significant results for the comparison between the Visual Decision and the Image task, the comparison between Image and Hertz tasks, Bada and Visual Decision tasks, and the subtraction between words and pseudowords of the Lexical Decision task in children with dyslexia compared to average readers. On this last task, Mann-Whitney's U and $p < 0.01$ revealed the greatest difference between both groups.

As seen on Table 4, the median of the subtraction between Visual Decision task and Image task N200 latencies for the frequent stimulus (p and similar-to inverted-T) was significantly much higher for dyslexic (*Mdn* = 4) than for control group (*Mdn* = -10, $p < 0.05$) at Pz (Central-Parietal) site. Control group had a longer latency in Image task than in Visual Decision task, but in the dyslexic group, latencies of both tasks had similar values (see Appendix 6). In control group, Visual Decision task's frequent stimulus was processed faster than Image's frequent stimulus at Parietal-Central (Pz). For the dyslexic group the result was the opposite: latency was prolonged when the Visual Decision task stimulus was presented compared to Image task's stimulus. This could mean that children with dyslexia invest less time in trying to recognize and categorize (Luck, 2005) visual non-linguistic (Image task) stimuli, compared to visual linguistic stimuli (Visual Decision task) when compared to average readers. Nevertheless, at the Temporal-Parietal site (TP10), the subtraction of latencies shows that children with dyslexia reported a lower median latency difference for the frequent stimulus compared to the control group, a finding that suggests variations in the voltages of each group according to a difference in the topographic distribution of the waves (Luck, 2005).

Table 4

Differences between the mean wave peak latencies

Task	Wave	Channel	Stimulus	Control			Dyslexic			*Mann-Whitney's U*	*Z*	*p value*
				Mdn	**Mean**	***SD***	**Mdn**	**Mean**	***SD***			
Visual Decision - Image	N200	TP10	p/similar-to-inverted T	8	12.533	12.176	2	4.93	27.763	53.500	-2.454	0.013*
		Pz		-10	-8.400	11.740	4	15.20	35.033	55.000	-2.390	0.017*
Hertz - Image	P100	PO10	similar to mirrored-L/ low tone	82	90.533	29.534	110	109.867	20.681	63.500	-2.033	0.042*
Bada - Visual Decision	P300	P7	da/p	138	155.200	42.378	194	188.400	32.029	59.000	-2.221	0.025*
Lexical Decision (Words-pseudowords)	N200	TP10	Words-Pseudowords	0	-2.533	8.766	4	5.200	7.123	42.500	-2.928	0.003**

Note. Mdn = Median; *SD* = Standard Deviation; *U* = Mann-Whitney U score, *Z* = Z score, $^{*}p < 0.05$, $^{**}p < 0.01$.

Median values of latencies subtraction of children with dyslexia were also higher than those of control group on the comparison between the infrequent stimulus of Hertz (low tone) and Image task (similar-to-mirrored-L) ($p < 0.05$) in P100 wave, at PO10, suggesting that the gap between the processing of visual stimuli and auditory stimuli is more pronounced in children with dyslexia than in average readers (Breznitz, 2002) with longer latencies to Hertz than to Image task's stimuli.

Higher median values for the children with dyslexia also occurred to the frequent stimulus of Bada (da) and Visual Decision tasks (p letter) ($p < 0.05$) at P7 in P300, which means that children with dyslexia took longer to process auditory linguistic stimuli than visual linguistic stimuli (Breznitz, 2002).

There was a relevant time difference for the processing of linguistic stimuli in children with dyslexia, with longer latencies to words than to pseudowords on the Lexical Decision task in N200 at TP10 ($p < 0.01$), whereas in the control group, there was no time difference between words and pseudowords processing. A result that aligns with those found by Miller-Shaul and Breznitz

(2004) in support of the slower SOP of individuals with dyslexia in phonological tasks (Breznitz, 2002).

Overall, there was a notable time difference between the processing of linguistic and non-linguistic visual stimuli, the processing of linguistic and non-linguistic visual vs. auditory stimuli, and the processing of words and pseudowords in children with dyslexia compared to average readers, supporting Breznitz (2002), as well as Miller-Shaul and Breznitz (2004) findings.

Differences between latencies of different peaks in all tasks

Differences between the mean latencies of components (P300-N200; N200-P100; P600-P300) were obtained for all tasks. These subtractions determined a value that accounts for a temporal gap between wave peak latencies, as a transition index between cognitive process stages —represented by each component—. After doing these calculations, only two significant measures were found. In the Hertz task, the difference between N200 and P100 latencies was significantly greater in average readers than in dyslexic readers at the Central-Occipital electrode (Oz) ($U = 60$, $Z = -2.179$, $p < 0.05$) when they heard the low tone (infrequent stimulus, $Mdn = 64$). The recognition and categorization of these tones (Luck, 2005; Vogel & Luck, 2000) was more detailed for average readers.

In the Bada task, a significantly longer latency ($U = 61$, $Z = -2.137$, $p < 0.05$) was found at the Central-Parietal channel (Pz), for the dyslexic group, to “ba” sound (infrequent stimulus, $Mdn = -202$), compared to typical readers (infrequent stimulus, $Mdn = -176$) when subtracting P600-P300 latencies. Delayed latencies of children with dyslexia in a task requiring segmentation and phonological analysis is a finding that emphasizes difficulties in phonological awareness of this group (Elbro, 1997; Liberman & Shankweiler, 1979, 1991; Snowling, 2000; Stanovich, 1988a, 1988b; Vellutino, 1979).

Conclusions

The main aim of this work was to study differences between the speed of processing (SOP) of the visual-orthographic and auditory-phonological modalities in children with dyslexia and average readers, by means of visual and auditory event-related potentials. To address this aim, we compared visual and auditory ERP's of children with dyslexia and average readers. The P100, N200, and P300 latency was significantly longer for both groups on Hertz task compared to Image task. Significantly prolonged P300 latencies in both groups were also found to Bada stimuli compared to Visual Decision task stimuli. Therefore, the processing of auditory linguistic and non-linguistic stimuli was more complex and delayed than the processing of visual linguistic and non-linguistic stimuli for both groups.

Further, there was a notable time difference between the processing of linguistic and non-linguistic visual stimuli, the processing of linguistic and non-linguistic visual vs. auditory stimuli, and the processing of words and pseudowords in children with dyslexia compared to average readers, supporting Breznitz (2002), as well as Miller-Shaul and Breznitz (2004) findings.

In addition, the lower P100 amplitudes of children with dyslexia to pseudowords, deeper N200 deflections to both words and pseudowords, and lower P300 amplitudes in dyslexic children compared to average readers when they were presented with words and pseudowords, argue in favor of the orthographic and phonological difficulties scientific literature has informed children with dyslexia have.

Limitations and Future Work

As this research is the first one in Spanish exploring the electrophysiological behavior of children with dyslexia using five different tasks (four of low level and one of high level), the extent to which these findings can be compared to previous work is limited.

We decided to report both the results from the frequent and the infrequent stimulus for each task, as we considered there might be differences generated from the presentation frequency of both stimuli, but in most of the investigations, only the infrequent stimulus measurements are reported.

An important constraint of this study was the small size and heterogeneity of participants due to difficulties on recruitment of children. Some children that were applied the neuropsychological assessment did not attend the EEG recording because the test location was too far from their homes, or due to religious beliefs of their parents.

Taking all these matters into account, we suggest continuing studying differences in the event-related potentials of children with dyslexia by manipulating linguistic and non-linguistic items of experimental tasks and recruiting a sample of a bigger size to collect more data and report their findings to a greater extent.

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Appendixes

Appendix 1

Analysis windows for automatic detection of individual peaks

Task	Wave	Analysis window (ms)
Bada	P300	487-587
	P600	680-800
Lexical Decision	P100	80-180
	N200	152-252
	P300	240-360
Visual Decision	P100	107-207
	N200	176-276
	P300	250-400
Hertz	P100	200-300
	N200	280-380
	P300	360-480
Image	P100	99-199
	N200	174-274
	P300	280-400

Source: Own work based on data obtained through BrainVision Analyzer software.

Appendix 2

Results of the Neuropsychological Assessment

	Control			Dyslexic					
Test	***Mdn***	***Mean***	***SD***	***Mdn***	***Mean***	***SD***	***U***	***Z***	***p-value***
ENI Battery									
Naming	10	9.933	2.314	12	11.733	2.154	62.500	-2.095	0.036*
Spelling	12	11.200	2.396	8	7.933	3.751	44.000	-2.865	0.003**
Syllables Reading	11	11.000	0.000	11	9.133	3.758	60.000	-2.944	0.006**
Sentences Reading	12	11.533	1.302	7	8.200	3.821	51.000	-2.832	0.005**
Sentences Comprehension	13	11.733	1.710	10	9.400	3.112	55.000	-2.443	0.013*

Number of Incorrectly Read Aloud Words (ENI) (Speed)	11	10.667	2.610	5	3.867	2.696	11.000	-4.242	0.000**
Words Read Aloud per Minute (ENI) (Speed)	9	9.600	2.501	6	4.800	2.541	15.000	-4.091	0.000**
Silently Read Words per Minute (ENI)	10	9.467	2.134	7	5.400	2.823	24.500	-3.692	0.000**
Words Copy (ENI)	12	11.200	2,042	9	7.267	3.218	34.500	-3.307	0.001**
Number of Words Copied per Minute (Speed)	9	9.067	2.492	7	6.467	1.922	47.500	-2.719	0.005**
PROLEC-R Battery									
Words Reading	30	29.867	0.516	28	27.133	2.850	15.500	-4.325	0.000**
Pseudowords Reading	29	28.800	1.474	26	23.867	5.680	46.500	-2.792	0.004**

Note. Mdn = Median; *SD* = Standard Deviation; *U* = Mann-Whitney U score, *Z* = Z score, **p* < 0.05, ***p* < 0.01. Measurements are reported according to scalar scores except for PROLEC's Words Reading and Pseudowords Reading tests.

Appendix 3

Comparison between groups per channel, per stimulus, and per task

Task	Wave	Channel	Stimulus	L/A	Control			Dyslexic			Mann-Whitney's U	Z	p value
					Mdn	*Mean*	*SD*	*Mdn*	*Mean*	*SD*			
Bada	P300	P7	ba	L	558.000	550.667	28.502	548.000	552.267	27.742	106.000	-0.271	0.797
				A	14138.000	14113.733	6525.020	10245.000	10181.333	8029.748	76.000	-1.514	0.137
			da	L	500.000	508.000	26.780	522.000	527.867	36.859	78.000	-1.441	0.154
				A	13343.000	13286.800	5634.217	14636.000	13146.600	7440.388	110.000	-0.104	0.935
		P8	ba	L	564.000	556.400	29.849	554.000	550.800	25.126	91.500	-0.872	0.394
				A	9488.000	8885.267	5739.461	12394.000	11438.333	7436.412	86.000	-1.099	0.285
			da	L	520.000	524.933	28.070	518.000	518.800	25.012	98.000	-0.602	0.559
				A	8944.000	9219.133	6442.822	12923.000	11739.467	7155.653	89.000	-0.975	0.345

Lexical Decision	P100	PO9	Words	L	126.000	124.667	5.538	122.000	125.867	10.211	99.500	-0.543	0.600
				A	12.844	14.611	9.322	13.645	4.252	15.703	75.000	-1.555	0.126
			Pseu-dowords	L	124.000	122.533	7.689	120.000	120.400	15.160	101.500	-0.458	0.659
				A	**16.110**	**16.413**	**7.971**	**8.738**	**4.240**	**12.736**	**55.000**	**-2.385**	**0.016***
		PO10	Words	L	126.000	125.867	6.479	122.000	125.067	8.876	91.500	-0.877	0.393
				A	16.718	17.649	11.914	10.954	6.911	15.935	80.000	-1.348	0.187
			Pseu-dowords	L	126.000	126.000	8.418	124.000	122.533	14.091	103.000	-0.398	0.703
				A	**19.547**	**19.817**	**10.324**	**10.926**	**7.435**	**13.313**	**51.000**	**-2.551**	**0.010***
	N200	TP9	Words	L	214.000	214.000	18.268	218.000	215.600	15.347	105.000	-0.312	0.766
				A	**-11.086**	**-13.935**	**9.473**	**-18.778**	**-21.311**	**8.613**	**60.000**	**-2.178**	**0.029***
			Pseu-dowords	L	212.000	210.933	19.077	212.000	213.067	16.731	111.000	-0.062	0.959
				A	**-14.809**	**-13.168**	**8.316**	**-19.021**	**-23.420**	**10.830**	**44.000**	**-2.841**	**0.004****
		TP10	Words	L	212.000	213.067	13.709	220.000	218.800	12.622	74.500	-1.581	0.117
				A	**-14.697**	**-17.890**	**8.186**	**-24.136**	**-26.707**	**9.825**	**41.000**	**-2.966**	**0.002****
			Pseu-dowords	L	212.000	215.600	15.896	212.000	213.600	13.736	110.500	-0.083	0.943
				A	-15.657	-18.095	8.153	-27.093	-26.326	5.873	45.000	-2.800	0.004**
	P300	P7	Words	L	326.000	323.333	27.315	324.000	315.333	33.574	101.000	-0.477	0.645
				A	**14.571**	**14.351**	**8.534**	**7.917**	**8.253**	**8.594**	**59.000**	**-2.219**	**0.026***
			Pseu-dowords	L	328.000	321.333	27.771	318.000	319.333	25.665	101.000	-0.477	0.645
				A	**14.624**	**16.869**	**7.976**	**7.102**	**9.350**	**8.488**	**52.000**	**-2.509**	**0.011***
		P8	Words	L	320.000	316.267	23.819	318.000	320.800	23.830	105.000	-0.312	0.767
				A	13.067	15.921	10.744	13.629	14.527	10.243	107.000	-0.228	0.838
			Pseu-dowords	L	322.000	317.600	22.881	316.000	321.733	25.172	109.500	-0.125	0.910
				A	17.286	17.903	9.604	13.672	14.914	10.031	93.000	-0.809	0.436

Visual Decision	P100	PO9	q	L	152.000	150.133	8.158	152.000	154.533	21.639	102.500	-0.416	0.689
				A	12.488	13.935	9.980	11.140	10.388	12.130	96.000	-0.684	0.512
			p	L	154.000	153.067	10.194	156.000	156.800	14.259	97.000	-0.645	0.531
				A	11.980	13.884	9.091	13.550	12.065	13.486	103.000	-0.394	0.713
		PO10	q	L	156.000	157.067	13.499	156.000	158.000	18.959	107.000	-0.229	0.830
				A	16.098	16.410	16.397	12.816	11.333	12.393	96.000	-0.684	0.512
			p	L	150.000	151.467	10.183	148.000	151.733	12.803	108.500	-0.167	0.878
				A	16.894	18.382	15.325	15.033	11.304	13.107	85.000	-1.141	0.267
		Oz	q	L	156.000	156.800	13.603	158.000	157.333	16.830	102.500	-0.416	0.689
				A	**14.980**	**16.301**	**6.648**	**8.480**	**10.833**	**8.908**	**63.000**	**-2.053**	**0.041***
			p	L	154.000	156.800	9.586	158.000	160.133	12.316	95.500	-0.708	0.491
				A	12.686	15.180	5.873	13.272	13.238	7.451	106.000	-0.270	0.806
	N200	TP9	q	L	234.000	239.867	16.792	230.000	232.533	28.188	96.500	-0.665	0.518
				A	-17.269	-23.116	26.003	-16.776	-14.671	9.159	93.000	-0.809	0.436
			p	L	234.000	235.067	15.727	236.000	240.133	16.809	96.500	-0.664	0.519
				A	-13.746	-18.360	29.689	-13.230	-11.945	9.446	112.000	-0.021	1.000
		TP10	q	L	236.000	240.133	13.637	238.000	236.533	18.860	101.000	-0.478	0.645
				A	-15.212	-19.627	18.484	-18.409	-16.585	7.565	105.000	-0.311	0.775
			p	L	238.000	242.667	14.276	236.000	236.133	19.146	87.000	-1.060	0.299
				A	-12.126	-17.242	20.742	-14.696	-15.580	7.036	82.000	-1.265	0.217
	P300	P7	q	L	346.000	346.800	21.617	342.000	344.267	36.189	105.000	-0.311	0.767
				A	10.924	8.338	8.672	7.867	7.771	6.779	104.000	-0.353	0.744
			p	L	358.000	352.800	38.350	346.000	339.467	29.340	80.000	-1.348	0.184
				A	7.119	9.349	6.767	6.013	7.223	8.494	94.000	-0.767	0.461
		P8	q	L	340.000	342.000	26.077	328.000	346.133	40.281	108.000	-0.187	0.862
				A	6.852	7.973	8.260	13.920	11.083	7.196	75.000	-1.555	0.126
			p	L	346.000	351.200	28.941	360.000	354	37.141	104.000	-0.353	0.735
				A	11.382	10.796	9.438	8.605	9.949	8.784	106.000	-0.270	0.806

Hertz	P100	PO9	Low tone	L	258.000	249.733	28.972	258.000	260.800	18.374	90.500	-0.914	0.372
				A	3.104	5.112	11.667	5.456	3.672	8.568	112.000	-0.021	1.000
			High tone	L	**232.000**	**241.200**	**24.829**	**252.000**	**254.800**	**18.249**	**62.500**	**-2.076**	**0.037***
				A	3.171	2.397	8.193	-3.226	1.145	8.399	97.000	-0.643	0.539
		P010	Low tone	L	**242.000**	**240.667**	**26.215**	**262.000**	**263.867**	**18.738**	**49.000**	**-2.637**	**0.007****
				A	2.745	3.559	13.695	6.262	6.243	11.235	100.000	-0.518	0.624
			High tone	L	234.000	241.467	29.321	248.000	251.867	23.182	83.000	-1.225	0.228
				A	0.199	-0.856	9.307	-0.498	3.160	8.971	95.000	-0.726	0.486
	N200	TP9	Low tone	L	316.000	316.933	20.783	316.000	319.333	18.278	103.000	-0.395	0.705
				A	-6.770	-6.262	12.982	-6.856	-11.058	19.998	107.000	-0.228	0.838
			High tone	L	310.000	308.000	14.383	312.000	315.067	22.752	98.500	-0.582	0.573
				A	-8.251	-8.799	9.375	-6.737	-7.969	12.606	101.000	-0.477	0.653
		TP10	Low tone	L	316.000	320.400	21.020	320.000	322.533	14.976	97.500	-0.624	0.545
				A	-7.996	-6.228	13.634	-5.593	-2.147	8.679	83.000	-1.224	0.233
			High tone	L	310.000	309.200	10.605	314.000	316.533	20.206	89.000	-0.978	0.338
				A	**-13.475**	**-10.658**	**9.639**	**-7.417**	**-4.711**	**7.112**	**62.000**	**-2.095**	**0.037***
	P300	P7	Low tone	L	394.000	404.800	25.855	404.000	407.600	26.973	103.500	-0.374	0.720
				A	8.702	11.924	7.671	9.813	10.561	6.638	105.000	-0.311	0.775
			High tone	L	398.000	402.667	22.254	406.000	411.600	39.715	101.000	-0.478	0.645
				A	9.615	8.183	5.261	10.585	7.611	8.581	105.000	-0.311	0.775
		P8	Low tone	L	420.000	420.400	34.436	418.000	419.067	35.350	111.500	-0.042	0.976
				A	10.735	10.451	7.848	11.322	11.250	6.596	99.000	-0.560	0.595
			High tone	L	394.000	403.333	28.662	404.000	415.467	39.645	95.500	-0.706	0.492
				A	11.126	10.030	8.259	9.067	7.515	5.974	98.000	-0.601	0.567

Image	P100	PO9	(similar-to-mirrored L)	L	146.000	147.333	10.217	150.000	147.600	11.593	104.000	-0.354	0.735
				A	2.376	6.338	12.439	3.988	5.524	11.719	100.000	-0.518	0.624
			(similar-to-inverted T)	L	144.000	144.133	7.308	148.000	146.400	17.158	96.000	-0.688	0.504
				A	12.496	11.115	12.475	8.213	7.400	8.998	85.000	-1.141	0.267
		P010	(similar-to-mirrored L)	L	150.000	150.133	10.460	156.000	154.000	13.774	90.000	-0.936	0.360
				A	8.699	8.109	12.203	11.193	5.271	13.182	98.000	-0.601	0.567
			(similar-to-inverted T)	L	146.000	146.000	9.827	146.000	144.133	15.296	110.000	-0.104	0.926
				A	11.884	12.447	14.227	8.869	7.465	12.772	98.000	-0.601	0.567
	N200	TP9	(similar-to-mirrored L)	L	234.000	236.400	16.991	234.000	234.800	16.541	105.000	-0.312	0.766
				A	-12.595	-15.101	9.164	-22.875	-23.467	23.470	79.000	-1.390	0.174
			(similar-to-inverted T)	L	232.000	235.200	18.910	236.000	234.800	15.781	111.500	-0.042	0.976
				A	-9.457	-10.705	7.750	-11.955	-19.273	23.173	73.000	-1.638	0.106
		TP10	(similar-to-mirrored L)	L	224.000	231.467	23.219	230.000	231.600	18.082	92.500	-0.831	0.417
				A	-11.859	-13.998	11.324	-18.251	-15.504	13.439	93.000	-0.809	0.436
			(similar-to-inverted T)	L	232.000	230.133	14.569	236.000	231.200	22.638	104.000	-0.353	0.736
				A	-13.672	-13.266	8.153	-14.444	-11.657	9.587	111.000	-0.062	0.967
	P300	P7	(similar-to-mirrored L)	L	360.000	354.267	36.885	356.000	348.800	31.962	101.500	-0.457	0.660
				A	5.594	6.569	7.598	5.643	7.045	6.436	107.000	-0.228	0.838
			(similar-to-inverted T)	L	340.000	347.467	28.550	332.000	344.267	41.513	103.000	-0.394	0.705
				A	6.414	7.732	7.666	4.642	6.629	5.698	95.000	-0.726	0.486
		P8	(similar-to-mirrored L)	L	358.000	352.533	37.106	360.000	361.600	28.588	97.500	-0.623	0.545
				A	9.974	7.485	10.415	12.808	9.852	9.382	100.000	-0.518	0.624
			(similar-to-inverted T)	L	360.000	356.933	27.660	370.000	352.800	42.216	111.000	-0.062	0.959
				A	7.575	5.246	8.048	8.226	8.827	6.377	93.000	-0.809	0.436

Note. *Mdn* = Median; *SD* = Standard Deviation; *U* = Mann-Whitney U score, *Z* = Z score, $^{*}p < 0.05$, $^{**}p < 0.01$ L = Latency; A = Amplitude. The first stimulus of each task is infrequent and the second one is frequent.

Appendix 4

Visual Intramodal Comparison between Visual Decision and Image tasks - P100

Visual Decision vs. Image - P100							
Control							
	PO9-1-A	**PO9- 2-L**	**Oz-1-L**	**Oz-1-A**	**Oz- 2-L**	**Oz-2-A**	**Pz-1-L**
Z	-2.442[c]	-2.906[c]	-2.079[c]	-2.385[c]	-2.610[c]	-.114[d]	-2.294[c]
p-value	0.012*	0.002**	0.036*	0.015*	0.006**	0.934	0.019*
Visual Decision Mdn	12.488	154.000	156.000	14.980	154.000	12.686	160.000
Image Mdn	2.376	144.000	152.000	11.583	150.000	15.112	152.000
Dyslexic							
	PO9-1-A	**PO9-2-L**	**Oz-1-L**	**Oz-1-A**	**Oz-2-L**	**Oz-2-A**	**Pz-1-L**
Z	-1.590[c]	-2.294[c]	-1.394[c]	-1.420[c]	-3.098[c]	-2.215[c]	-.524[c]
p-value	0.121	0.019*	0.172	0.169	0.001**	0.026*	0.624
Visual Decision Mdn	11.140	156.000	158.000	8.480	158.000	13.272	158.000
Image Mdn	3.988	148.000	152.000	10.588	146.000	10.431	154.000

Note. Z = Wilcoxon Signed Rank test value, $^{*}p < 0.05$, $^{**}p < 0.01$ L = Latency; A = Amplitude. 1 = Infrequent stimulus (q letter, low tone), 2 = Frequent stimulus (p letter, high tone). [c] = it is based on negative ranks, [d] = it is based on positive ranks.