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DYSLEXIA AND THE PERKS OF BEING BILINGUAL: A STUDY ON THE NEUROBIOLOGY OF READING WITH fMRI

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Abstract

The objective of the present study was to investigate reading performance and brain activation associated with reading for bilingual and monolingual dyslexics (DDB-DDM), and typical bilinguals as Controls (C). The behavioral results showed that DDB outperformed DDM in all reading components in Portuguese. In the tasks applied in English, there was no significant difference in the performance of DDB compared to C. The results of the brain imaging for the task in Portuguese showed C presented significant activation of the left occipitotemporal and left inferior frontal gyrus while reading words. DDB and DDM, in turn, showed deactivation of left temporoparietal region and no significant activation in the left occipitotemporal region or left inferior frontal gyrus. For the FAST LOC task, DDB showed hypoactivity in the Visual Word Form Area (VWFA) during word reading, both in English and Portuguese. The findings provide evidence for a possible positive impact of bilingualism on the reading performance of dyslexics.

Keywords: bilingualism; dyslexia; VWFA; reading; fMRI

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Introduction

Dyslexia is the alternative term used in reference to a pattern of learning disabilities with impairment in reading and spelling. The DSM-5 (Diagnostic and Statistical Manual of Mental Disorders) defines dyslexia as a specific learning disorder with impairment in reading. According to Shaywitz and Shaywitz (2020) dyslexia is a disorder of neurobiological origin that presents as a severe difficulty in learning to read. This disorder is related to a deficit in the association between phonemes and graphemes on the part of learners, who hesitate at each syllable, mix up sounds, and end up trying to guess words (Dehaene, 2012).

The functional brain activation differences associated with developmental dyslexia, relative to good readers, have been replicated across different languages. Dyslexia is associated with significantly less activation of the well-known network of left-hemisphere regions associated with reading, including the left occipitotemporal region (VWFA), left angular gyrus (generally left temporoparietal), and left inferior frontal gyrus in different writing systems (Buchweitz et al., 2018; Wei et al., 2015; Hoeft et al., 2011; Paulesu et al., 2001; Shaywitz et al., 2002)

Regarding bilingualism, reading, and dyslexia, there is a hypothesis that suggests that learning to read in two languages differing in orthographic consistency leads to a cross-linguistic modulation of reading and spelling processes, known as "*Grain Size Accommodation hypothesis*" (Lallier; Carreiras, 2017). With respect to reading processes, this hypothesis offers a framework that allows to predict how bilingualism may interact with reading processes in children and adults with or without dyslexia. The authors also endorsed the existence of cross-linguistic transfer from more consistent to less consistent orthographies. Furthermore, according to Vender et al., (2018) there is evidence for a bilingual advantage for dyslexic readers. Dyslexic bilinguals seem to further develop their morphological and metalinguistic abilities compared to monolingual dyslexics, surpassing monolingual children with no reading disabilities in some conditions.

Driven by the hypothesis that learning a second language (L2) since childhood could bring benefits to individuals with dyslexia, the goal of the present study was to investigate reading performance in Portuguese-English and the brain activation associated with reading words by bilingual and monolingual dyslexic readers, and typical bilinguals as Controls. This was the first brain imaging study to investigate brain function in bilingual (Portuguese-English) dyslexic children in Brazil.

Finally, we emphasize that the present research is part of an umbrella project of the Brain Institute of Rio Grande do Sul, entitled ACERTA (Assessment of Children at Risk of Learning Disorders).

The brain circuitry involved in reading in different languages

The cognitive science of reading advocates that learning to read and write is not natural nor spontaneous. One does not learn to read as one learns to speak.

Human language is natural when it comes to speech, and we are born biologically programmed to develop oral language. There is an innate neural network for oral language processing that is similar across languages (Rueckl et al., 2015). However, reading and writing need to be explicitly and systematically taught (Perfetti et al., 2005; Dehaene, 2012). What is more, learning to read is associated with systematic adaptation of a brain area in the occipitotemporal region. At first, this area is involved in associative visual processing of faces and objects. As individuals learn to read, it becomes specialized in the identification of the visual form of words. Due to this new function, the area has been coined the Visual Word Form Area-VWFA (Cohen et al., 2002; Dehaene, 2012). The activation of this region is a brain marker of fluent reading development (Dehaene & Cohen, 2011; McCandliss, Cohen, & Dehaene, 2003).

Regarding the brain circuitry involved in reading, Turker and Hartwigsen (2021) aimed to summarize the results of 78 non-invasive brain stimulation studies (NIBS). The aim was to investigate the causal involvement of brain regions for reading processing and then connect these results to a neurobiological model of reading. The results provide evidence for a dual stream neurobiological model of reading, in which a dorsal stream (left parietal-temporal and inferior frontal areas) processes unknown words and pseudowords, and a ventral stream (left occipitotemporal and inferior frontal, with assistance from the angular gyrus and anterior temporal lobe), processes known, high-frequency words. This study corroborates Ellis' Dual-Route model (1995). Ellis advocates that during the process of word identification, the use of the Lexical route allows faster access to the mental lexicon because it is a procedure of direct access to meaning from the graphic structure. In contrast, the Nonlexical Route is a sequential procedure, at least at the beginning of reading development, and therefore, slower than the previous one.

Zhan et al. (2023) conducted a recent study whose aim was to explore whether bilingual readers have distinct cortical patches dedicated to different languages. The researchers employed high-resolution 7-tesla functional magnetic resonance imaging (fMRI). Their study involved 21 English-French bilinguals, and the unsmoothed 1.2-millimeter fMRI scans revealed that the VWFA is actually comprised of multiple small cortical patches, each exhibiting high selectivity for reading. Interestingly, these patches displayed a word-similarity gradient that extended from the posterior to the anterior regions, and remarkably, this gradient was nearly identical for both English and French.

In another aspect of Zhan et al.'s study, the researchers examined 10 English-Chinese bilinguals. While most of the word-specific patches demonstrated similar reading specificity and word-similarity gradients for both Chinese and English, there were additional patches that responded specifically to Chinese writing. These patches also exhibited a response to faces, which was an unexpected finding.

These results indicate that the visual cortex of bilingual individuals can be influenced differently when acquiring multiple writing systems. In some cases,

this divergence leads to the development of cortical patches that are specialized for a single language.

Dyslexia and the perks of being bilingual

Dyslexia manifests in reading different languages and orthographies. As previously presented, neuroimaging studies have advanced the understanding of the neurobiology of dyslexia with evidence that has been replicated in several studies and different languages. For instance, a meta-analysis of studies of dyslexics and functional neuroimaging shows that the neurocognitive dysfunctions of developmental dyslexia are common to readers of different languages (Martin et al., 2015). Slow and labored reading is associated with a universal dysfunction in the occipitotemporal and temporoparietal regions and the left inferior frontal gyrus.

In a neuroimaging study of dyslexic readers (French, English, and Italian), it was suggested that there is a neurobiological unity to cultural diversity; in all three languages, the dyslexics showed hypoactivity in posterior regions, including the occipitotemporal region and the temporoparietal region (Paulesu et al., 2001). The hypoactivity suggests a disengagement of regions typically involved in reading in different languages.

For the purpose of the present study, we focus on the occipitotemporal region, coined as the visual word form area-VWFA (Dehaene et al., 2010; Dehaene & Cohen, 2011; Dehaene, 2012; Pegado et al., 2014), temporoparietal, and left inferior frontal gyrus, also known as Broca's area. As for the languages chosen for this study, Brazilian Portuguese (transparent) and English (deep) were used in the tasks.

Reading difficulties may vary according to the language (transparent and deep orthographies[1]). In the past, learning a second language was seen as something somehow undesirable for dyslexic individuals (Shaywitz, 2008). However, recent studies show otherwise.

In a study conducted by Bree et al. (2017), the authors found that the bilingual group performed similarly or better than the monolingual group, and that the incidence of poor word readers was numerically lower in the bilingual than in the monolingual dyslexic groups. The findings prompt questions about whether bilingual children, in general, might have a general advantage - bilingual cognitive advantages - or a specific advantage related to reading that aids in learning to read. Additionally, it raises the question of whether bilingual children with Developmental Language Disorder (such as dyslexia) can compensate for their word reading difficulties.

Examining seventeen studies on the relationship between bilingualism and phonological processing in dyslexic children, Chiquito et al. (2019) reached a noteworthy conclusion. They found that bilingualism could have positive effects on phonological processing skills in dyslexic children. However, the extent of

this effect depended on factors such as language proficiency, age of onset of bilingualism, and language characteristics.

Bruin et al. (2020) delved into the relationship between bilingualism, phonological awareness, and dyslexia in a group of dyslexic and typically developing children. Their findings indicated that bilingualism might offer a protective effect against dyslexia by enhancing phonological awareness skills, especially in the second language. Additionally, Leclercq et al. (2020) analyzed sixteen studies and discovered that bilingualism does not necessarily worsen reading difficulties in children with dyslexia. In fact, they suggested that early bilingualism might have protective effects on language and reading development.

Furthermore, in 2021, Xie et al., conducted a meta-analysis exploring the relationship between bilingualism and reading disorders. Their findings indicated that bilingualism was associated with better reading outcomes in both typically developing children and those with reading disorders. However, it is important to note that the effect size was small and contingent on factors such as language proficiency and age of onset of bilingualism.

Finally, López-Espejo et al. (2021) examined twelve studies focusing on the link between bilingualism and cognitive outcomes in children with dyslexia. Their results revealed that bilingualism was associated with improved cognitive outcomes, particularly in attention and executive function, in children with dyslexia.

The six studies presented earlier provide evidence suggesting that being bilingual may have a protective effect against dyslexia. When individuals are exposed to different spelling systems while learning to read, their brains exhibit a form of adaptability specific to spelling. This means that the brain can adjust and recognize various spellings of the same sound. In essence, the brain's capacity to adapt and recognize different spellings plays a crucial role in reading and can be influenced by factors such as exposure to different languages and writing systems, as well as individual cognitive and linguistic abilities (Buetler et al., 2016).

In sum, it is of utmost importance to understand the factors influencing the reading abilities of bilingual individuals and to identify the differences compared to monolinguals. Such knowledge will play a significant role in enhancing interventions and remediation strategies for individuals with dyslexia.

Methods

This section presents information about the participants of this study, the recruitment process, the instruments used, the procedures for data collection, and the statistical and neuroimaging analysis performed after data collection.

Participants

We understand bilingualism as the use of two or more languages or dialects in everyday life, according to need and with different levels of proficiency (Grosjean; Li, 2013). In our study, to be considered "bilingual", the participant should meet the

following requirements: be Brazilian, native speaker of Portuguese and a student of English as a foreign language since the age of 6 (or less), have formal exposure to the language from 4 to 5 times a week, have a proficiency certificate from Cambridge University or other (mandatory component in the school where most of the participants study). The participants considered "monolinguals" should fulfill the following requirements, be Brazilian, native speakers of Portuguese, have started learning English from 5th grade on, have formal exposure to the English language twice a week or less.

The 8 bilingual readers (typical and dyslexic) were recruited at a private school with an extended English curriculum. The 4 monolingual dyslexic readers were recruited at the pro bono reading clinic supported by the project (ACERTA) and studied in private schools. The goal of the clinic is to establish a cohort of dyslexic readers of Portuguese and investigate the neurological bases of dyslexia in the language. Regarding the severity of the disorder, three participants exhibited a moderate degree of dyslexia, and one presented a severe degree (bilingual dyslexic group); two participants exhibited a moderate degree of dyslexia, and two presented a severe degree (monolingual dyslexic group).

The study included 12 participants (8 girls and 4 boys), whose mean age was 14.8 (ages 13 to 18 years). Dyslexic participants (monolinguals and bilinguals) and bilingual good readers were matched by age, I.Q. (WISC-III), grade and proficiency in English (according to their proficiency certificates from Cambridge University), as shown in Tables 1 and 2. The data from the anamnesis indicated that the estimated average IQ of the participants is 111.67 (above average). The average monthly family income for the groups is as follows: DDB (13.000 Brazilian *reais*), DDM (5.800 Brazilian *reais*), and C (12.800 Brazilian *reais*). All participants attended private schools in Porto Alegre.

All participants signed the informed consent form. The study was approved by the Pontifical Catholic University of Rio Grande do Sul Research Ethics Committee (number 30895614.5.0000.5336).

The participants were divided into three groups, as follows: **Experimental Group 1 (DDB) –** dyslexic bilinguals. Four (4) participants between 13 and 18 years old. **Control Group (C)** - bilinguals with typical reading development**.** Four (4) participants between 13 and 18 years old. **Experimental Group 2 (DDM) –** dyslexic monolingual. Four (4) participants between 13 and 18 years old.

Table 1. Participants' Matching

Participants	Age	IQ
DDB1, DDM1, C1	18,18,17	117,110,123
DDB2, DDM2, C2	15,15,15	109,103,116
DDB3, DDM3, C3	14,15,14	112,109,118
DDB4, DDM4, C4	13,13,13	106,102,115

Table 2. Participants Mean Age and Mean IQ

	Mean Age	SD	Mean IQ	SD
Participants	14,8	1,8	112	6,3

According to the results found in the Language History Questionnaire for Bilinguals (Scholl & Finger, 2013), DDB and C participants started learning English in school at the age of 5/6, and one DDB participant at the age of 3. Participants' proficiency level in English varied from Intermediate to Advanced, according to the Common European Framework of Reference for Languages (CEFR).

Materials and Procedures: Behavioral Data

We chose reading tasks with similar constructs in both languages (Portuguese- English).

Tasks in Portuguese

The reading tasks presented in this paper are Fluency (*Fluência de leitura*) and Word Reading (*Precisão de Leitura*). The procedures are detailed in Costa et al. (2015).

Tasks in English: Woodcock - Johnson Achievement Battery - III (WJ - III)

The tasks from WJ-III used were: I. Letter Word Identification (Test 1), which evaluates recognition and production of letters and words (76 in total) presented by level of difficulty; II. Reading Fluency (Test 2), which measures reading fluency; the participant receives a sheet of paper with ninety-eight (98) sentences and has to read and answer yes or no within three minutes, and III. Word Attack (Test 13), which evaluates the reading aloud of a list of 32 pseudowords.

Behavioral data analysis

We investigated the confidence interval (CI) for reading performance scores to compare performance across groups.

Materials and Procedures: fMRI parameters

Data was collected on a GE HDxT 3.0T MRI scanner with an eight-channel head coil. Three MRI sequences were acquired: a T1 structural scan (TR/TE = 6.16/2.18 ms, isotropic 1 mm3 voxels); two task-related functional FMRI

EPI sequences (run 1 = 8 min; run 2 = 8 min 04 s). For the task EPI sequence, we used the following parameters: TR = 2000 ms, TE = 30 ms, 29 interleaved slices, slice thickness = 3.6 mm; slice gap = 0.3 mm; matrix size = 64 × 64, FOV = 220 × 220 mm, voxel size = 3.75 × 3.75 × 3.90 mm. During the scan, real-time motion detection software was used to monitor participant cooperation. In case participants presented more than 0.9 mm of motion in more than 20 TRs before completing the run, we interrupted the experiment and ran the task again. We made one attempt to re-run the task if it was stopped due to excessive head motion.

Experimental design in fMRI

Word-reading task in Portuguese

The reading task in Portuguese consisted of word and pseudoword reading adapted from a test for Brazilian children (Salles et al., 2013). The stimuli were divided into two series of 30 items each. Words and pseudowords were presented on the screen, one at a time, for seven seconds each. Participants were instructed to read the words and use the two yes/no mouse devices to answer whether the word existed or not. The response time (in milliseconds) and accuracy for reading each word were collected.

Fast language Localizer: FAST LOC (Tasks for bilinguals)

Fast Loc (in Portuguese and English) is a reading and audio task, divided into two parts. The task consists of 4 types of blocks (2 with visual stimuli and 2 with auditory stimuli): written words, word audios, "symbols" (written word with *wingdings font*, for instance ♒●●□♑◆🖂♦), and "synthesized" and unintelligible audios (vocoded speech). The last two blocks serve as distractions. The blocks are randomly distributed, and each block consists of 4 stimuli. The visual stimuli (written words and "symbols") appear on the screen for 250 milliseconds each. The auditory stimuli (word audio and vocoded speech) last for 800 milliseconds each. When the auditory stimuli are presented, the participant does not receive any visual stimulus (black screen on the monitor). During the task, the participant should mentally read the word or symbol that appears on the screen. If it is a sound, the participant should try to listen to and understand what was heard. For the present paper, only the reading data will be presented.

fMRI analysis

Functional data were preprocessed using AFNI's (http://afni.nimh.nih.gov/) afni_proc.py program (Cox, 1996). Preprocessing included slice-time and motion correction, smoothing with a 6-mm FWHM Gaussian kernel, and a nonlinear spatial normalization to 3.0 x 3.0 x 3.0 mm voxel template (HaskinsPedsNL template). TRs with motion outliers (>0.9 mm) were censored from the data. The criteria for

exclusion due to head motion were excessive motion in 20% of the TRs. The average head motion for each group for the participants included in the study, in the word-reading paradigm, was: DYS M = 0.16 (SD = 0.08), TYP M = 0.18 (SD = 0.15). One participant from each group was excluded due to excessive head motion.

First level analysis included modeling regressors for the conditions for each of the three types of word (regular words, irregular words, and pseudowords), and for the fixation condition, convolved with the canonical hemodynamic response function as implemented in AFNI (Cox, 1996). The 7-sec rest periods were not explicitly modeled. T-test analyses were carried out to compare the distribution of activation between the two groups using a random-effects model and the contrast images for all word types versus fixation. To correct for multiple comparisons, the 3dClustSim program was used to calculate a corrected p-score of <0.05: following the calculation, the analyses were carried out for a cluster of $p < 0.005$ with a minimum cluster size = 62 voxels (1674 μl). Participant age was entered as a covariate in the analyses between groups to control for any effects due to the average one-year difference in age between the groups.

Seed-based analysis of activation was performed. A spherical seed was drawn to investigate the activation between reading-related regions of the left-hemisphere and the remainder of the brain. The following areas of the brain were investigated: (all radii 8.0 mm; all coordinates Montreal Neurological Institute, MNI) left fusiform gyrus/visual word form area (x = −44, y = −58, z = −15); left angular gyrus (x = −45, y = −64, z = 33); left inferior frontal gyrus (x = −44, y = 24, z = 2); left middle temporal gyrus (x = −52, y = −19, z = 7; left superior temporal gyrus (x = −51, y = −17, z = 0).

Results

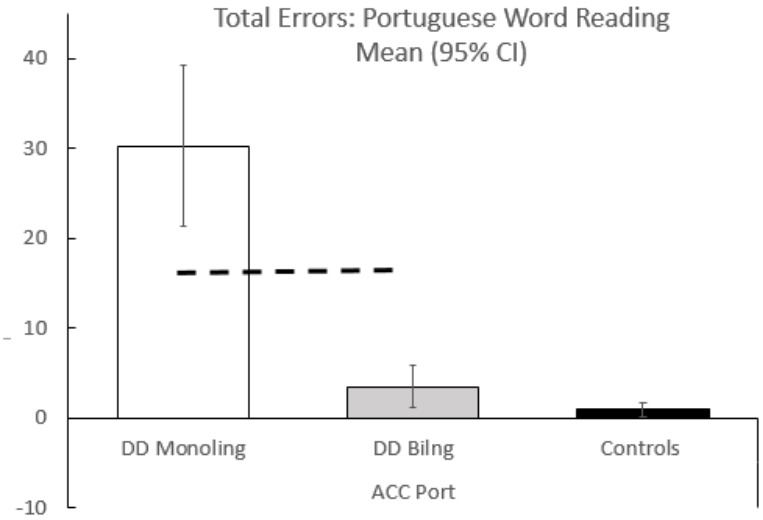
In this section, we present the results of the behavioral data from this study, followed by the results obtained from the functional neuroimaging tests.

Behavioral data - Tasks in Portuguese

The results of the Portuguese reading tests suggest that dyslexic bilinguals performed better than dyslexic monolinguals, but worse than the control group in all tasks in Portuguese.

In the first task, Word Reading (*Precisão de Leitura*), participants were asked to read aloud a list of 50 words and pseudowords. Taking the Control group as the baseline for our analysis, it is noteworthy that the average results of the DDB group (3 errors) are closer to the C group, when compared to the DDM group (29 errors). The DDM group exhibited a significantly higher number of errors compared to the C group. In sum, the performance of the DDB group is closer to the C group than the result obtained by the DDM group, highlighting the advantage of bilingual dyslexics over monolinguals in reading accuracy tasks, as shown in Figure 1.

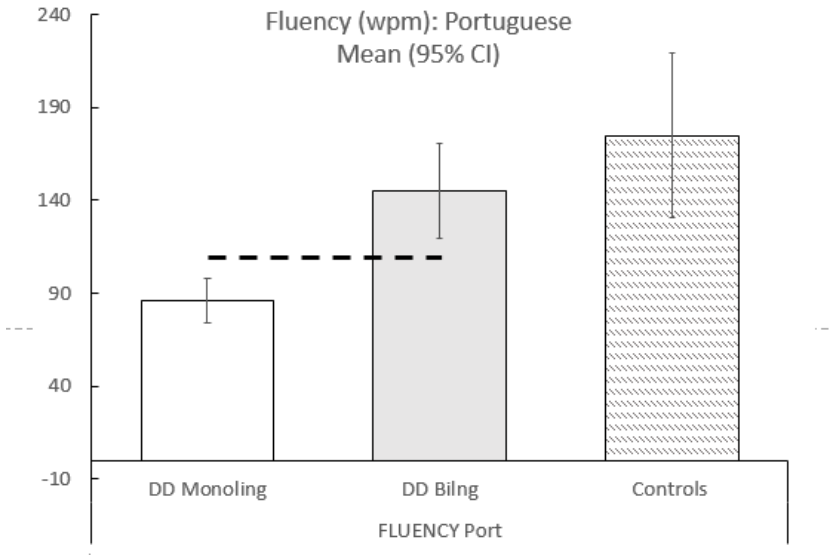
Figure 1. Results of the Word Reading task in Portuguese



Total errors in word reading task. Bar graphs represent mean, and the error bar represents 95% confidence interval for p<0.05. Dashed line inserted to illustrate difference between upper and lower value for CI for DD Bilinguals and DD Monolinguals.

The second task, Fluency (*Fluência de leitura*), involves reading a text while measuring the number of words read per minute. As we can see in Figure 2, the DDM group showed an average of 86 words read per minute (SD 12.43), whereas the DDB group showed an average of 145 words read (SD 25.74). As for the C group, participants presented an average of 175 words read (SD 45.08). Taking the C group as the baseline for our analysis, we once again highlight that the results obtained by the DDB group are closer to the C group when compared to the DDM group. The latter demonstrated significantly lower performance compared to the C group.

Figure 2. Results of the Fluency task in Portuguese



Reading fluency in words per minute (WPM). Bar graphs represent mean, and the error bar represents 95% confidence interval for p<0.05. Dashed line inserted to illustrate difference between upper and lower value for CI for DD Bilinguals and DD Monolinguals.

Behavioral data - Woodcock - Johnson Achievement Battery - III

In the tasks performed in English, the DDB group showed an average of 5 more errors in comparison to the C group (which is lower than the results obtained between the same groups in the tasks in Portuguese).

Figure 3 shows the results of the "letter word identification" task. Participants were asked to read 76 low and high-frequency words in English. The DDB group showed an average of 15 errors (SD 3.86), while the C group presented an average of 10 errors (SD 4.24). Bar graphs represent mean, and the error bar represents 95% confidence interval for $p<0.05$.

Figure 3. Results of the Letter Word Identification task

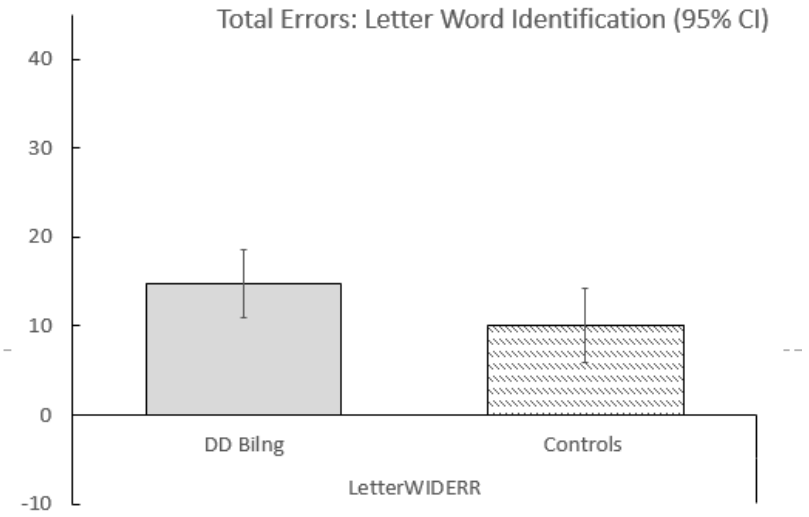
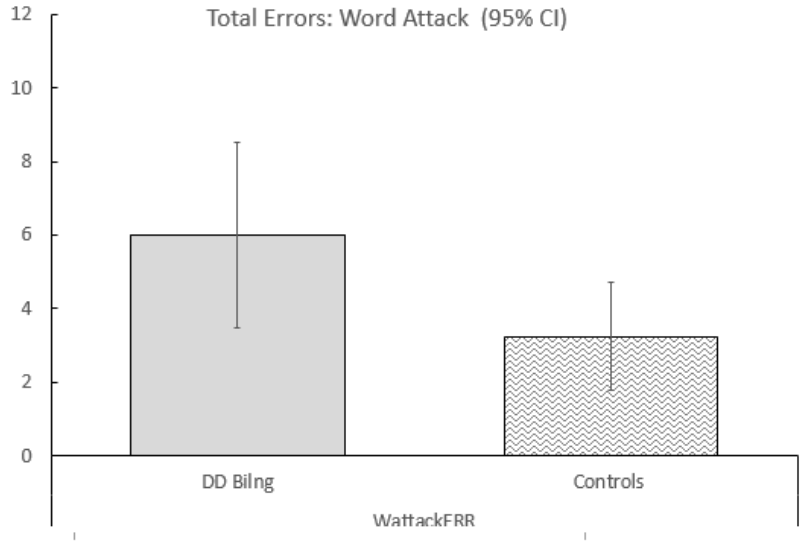


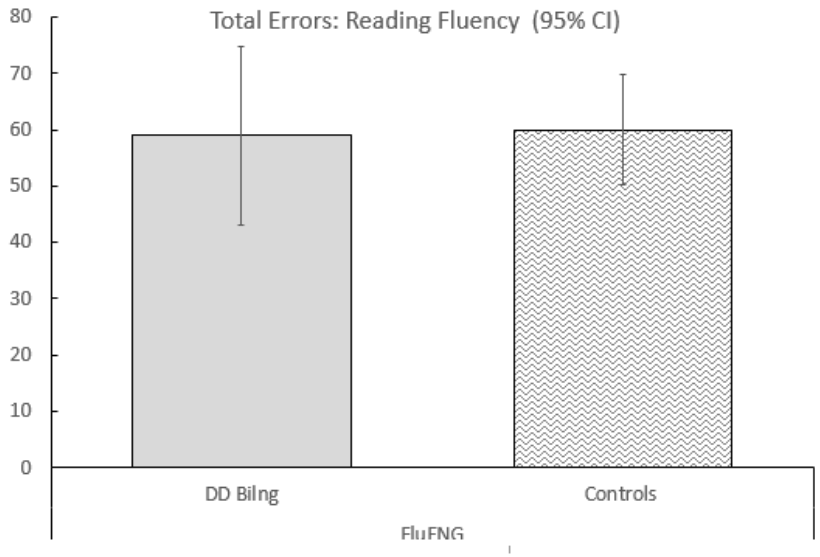
Figure 4 shows the results of the "Word Attack" task. Participants were asked to read 32 pseudowords in English. The DDB group showed an average of 6 error for pseudowords (SD 2.58), while the C group presented an average of 3 errors (SD 1.50). The differences are not significant despite a tendency towards poorer performance among the DDB group. Bar graphs represent mean, and the error bar represents 95% confidence interval for $p<0.05$.

Figure 4. Results of the Word Attack task



Finally, in the last task, Reading Fluency in English, participants were given 3 minutes to read as many as 98 sentences in English and choose true or false for each of them (based on their understanding of the sentences). As we can see in Figure 5, the DDB group showed an average of 59 errors (SD 16.18), while the C group presented an average of 60 errors (SD 10.03); 1 error difference (2% below the control group). Bar graphs represent mean, and the error bar represents 95% confidence interval for $p<0.05$.

Figure 5. Results of the Reading Fluency task in English



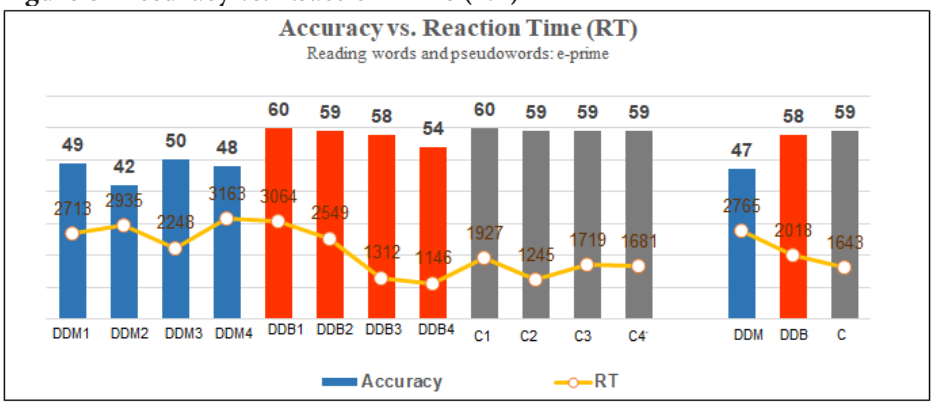
In sum, in the Letter-word Identification, Fluency, and Word Attack tasks, applied in English, the results suggest that there was no significant difference in the performance of dyslexic bilinguals compared to typical bilingual readers. The scores of the DDB group were closer to, but rarely higher than, the C group.

Experimental design in fMRI

Results of the Word-reading task in Portuguese

In reading words and pseudowords (Salles et al., 2013) during the neuroimaging exam, the accuracy of bilingual dyslexics (mean = 58 hits; SD = 2.6) and controls (mean = 59 hits; SD = 0.5) did not differ, while the accuracy of monolingual dyslexics was lower than the other two groups (mean = 47 hits; SD = 3.5), as shown in Figure 6, below.

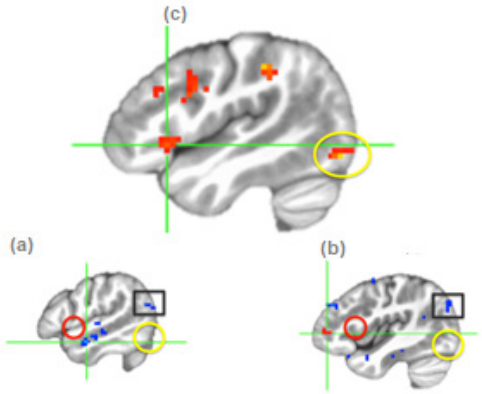
Figure 6- Accuracy vs. Reaction Time (RT)



The difference between dyslexic bilinguals and their controls appears in response time, i.e., dyslexic bilinguals have similar accuracy to controls on the task, but this depends on more processing time: DDB = 2018 ms (SD = 937); C = 1643 ms; (SD = 286); dyslexic monolinguals are the slowest of all, DDM = 2765 ms (SD = 390).

Concerning neuroimaging results for the same task, the brain activation for each group shows that controls had a significant activation of left occipitotemporal and left inferior frontal gyrus while reading words, as shown in Figure 7.

Figure 7. Activation of left-hemisphere brain network in controls and developmental dyslexia



Activation for reading words and pseudowords (SALLES et al., 2013) (a), bilingual dyslexics (b) and monolingual dyslexics (c) Controls on the lexical decision task. For the

controls, the green rod target indicates significant activation in Broca's area. Significant differences between the reading and control conditions in the other two groups was not found (red, anterior ellipses highlight the absence of activation); the yellow, posterior ellipses highlight activation in the occipitotemporal region in the controls, and that it is also absent in the dyslexics. The rectangles in brains (a) and (b) mark the deactivation of the temporoparietal region in dyslexics. Images taken of the left hemisphere, representing activation in each group (AFNI; $p<0.05$ corrected for multiple comparisons).

Dyslexic monolinguals and bilinguals, in turn, showed deactivation of left temporoparietal region and no significant activation in left occipitotemporal region or left inferior frontal gyrus. These findings align with Shaywitz's work (2008), who speaks of the neural signature of dyslexia. According to the author, significant distinctions in brain activation patterns were observed between the dyslexic and non-dyslexic groups, with dyslexic readers displaying decreased activation in posterior areas (such as Wernicke's area and the angular gyrus) and increased activation in an anterior region (the inferior frontal gyrus). Shaywitz's findings suggest that the underlying issue in dyslexia is primarily related to phonological processing, and these distinctive brain activation patterns could serve as a neural signature for this impairment.

Results of the FAST_LOC (Tasks for bilinguals)

For the VWFA, which is a brain marker of reading proficiency, the results showed a hypoactivity (including deactivation) in this region during word reading, both in English and Portuguese. However, in Portuguese, dyslexic individuals presented more activity in the VWFA than the controls. Unlike English, Portuguese is considered a more transparent language (grapheme-phoneme correspondence). The results suggested that the apparent superiority in the performance of the DDB group in Portuguese tasks may be related to the issue of orthographic depth (English being deeper and Portuguese being more transparent). Transparent orthographies are often considered to be easier for beginning readers because the relationship between letters and sounds is more straightforward and predictable. In contrast, deep orthographies can pose challenges for learners, as they require more complex and abstract mapping of written symbols to speech sounds.

Figure 8. Activation of the VWFA in Fast Loc tasks in English and Portuguese

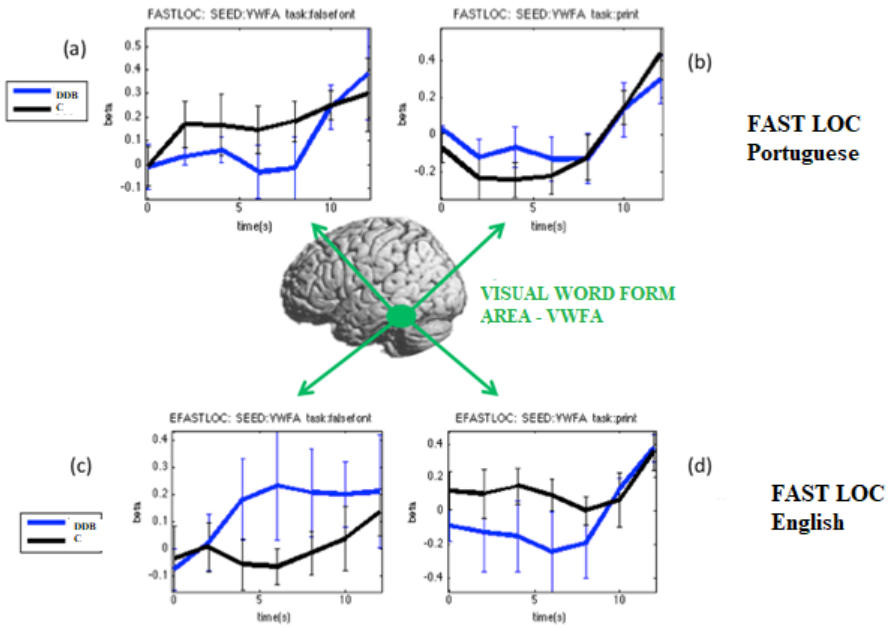


Fig.8. Activation for the VWFA in Fast Loc tasks in English and Portuguese: (a) activity in the task with fake font during the Portuguese task; (b) activity in the task with words in Portuguese; (c) activity in the task with fake font during the English task; (d) activity in the task with words in English. The beta values (y-axis; regression coefficient) are extracted for the previously marked and described regions of interest. Time (x-axis) represents the time in the experiment. Each graph represents the average betas for all participants and across all items (all words).

The results demonstrated an inverse behavior in the comparison between controls and dyslexic individuals. In the Portuguese task, controls presented less activation than dyslexic individuals in word reading in the VWFA [Figure (b), Figure 8 above]; however, in English, this behavior was reversed. Dyslexic individuals presented significantly more activation during the processing of non-words [Figure (c)], but significantly less during word processing [Figure (d)]. Further study on neural mechanisms in dyslexic bilinguals is suggested to better understand the neural processes that underlie this difference in activation.

Discussion

In this section, we present the discussion regarding the behavioral data from this study, followed by the discussion of the functional neuroimaging tests, and some final remarks.

Behavioral data: Reading tasks in Portuguese and English

Learning to read is a major cognitive challenge for all children, whether monolingual or bilingual, especially if learners encounter the obstacle of dyslexia.

Dyslexia is conceptualized as a specific learning disorder of neurobiological origin, characterized by difficulties in accurate and/or fluent word recognition, decoding, and spelling skills. Secondary consequences include problems in

text comprehension, as well as reduced reading experience that may hinder an individual's increased vocabulary knowledge and encyclopedic knowledge (Siegel, 2013; Dehaene, 2012; Pugh, Mccardle, 2009).

However, children with dyslexia are able to learn to read/write, provided new learning strategies are at place. According to Snowling, Hulme and Nation (2020), intensive training in the ability to associate phonemes with letters can positively influence the reading ability of dyslexic children. What is more, recent studies (López-Espejo et al., 2021; Xie et al., 2021) provide evidence suggesting that bilingualism may have a protective effect against dyslexia. When individuals are exposed to different spelling systems while learning to read, their brains exhibit a form of adaptability specific to spelling. This means that the brain can adjust and recognize various spellings of the same sound. Lallier and Carreiras (2017) also endorsed the existence of cross-linguistic transfer from more consistent to less consistent orthographies (in this case, Portuguese to English).

Driven by the hypothesis that learning an L2 since childhood could bring benefits to individuals with dyslexia, the goal of the present study was to investigate reading performance in Portuguese-English by bilingual and monolingual dyslexic readers, and typical bilinguals as controls. The behavioral results showed DDB outperformed DDM in all reading components in Portuguese. In the tasks applied in English, there was no significant difference in the performance of DDB compared to Controls. These findings suggest a positive impact of bilingualism on the reading performance of dyslexics.

The participants in this study started learning English before the age of 6. It can be inferred that their exposure to a foreign language in the early stages of learning to read may have had a positive impact on learners' phonological abilities in English. Another factor that may contribute to a bilingual advantage in dyslexia is that bilingual individuals often access linguistic and orthographic representations in both languages, and this constant interaction between the two languages would facilitate bidirectional sharing (or transfer) of knowledge between the languages, thus facilitating reading and writing in L2 (Kovelman; Bisconti; Hoeft, 2016).

With regard to the test performed in English, dyslexic bilinguals performed similarly to controls. The scores of the DDB group were closer to, but rarely higher than, the C group. These results corroborate to Bruin et al.'s (2020) findings that indicate bilingualism might offer a protective effect against dyslexia by enhancing phonological awareness skills, especially in the second language.

Neuroimaging data

As stated in the introduction of this paper, the functional brain activation differences associated with developmental dyslexia, relative to good readers, have been replicated across different languages. Dyslexia is associated with significantly less activation of the well-known network of left-hemisphere regions associated with reading, including the left occipitotemporal region (VWFA), left

angular gyrus (generally left temporoparietal), and left inferior frontal gyrus in different writing systems (Buchweitz et al., 2018; Wei et al., 2015; Hoeft et al., 2011; Paulesu et al., 2001; Shaywitz et al., 2002).

The present study proposed two different tasks using fMRI. In the first one, reading words and pseudowords (Salles et al., 2013), the accuracy of bilingual dyslexics (mean = 58 hits; SD = 2.6) and controls (mean = 59 hits; SD = 0.5) did not differ, while the accuracy of monolingual dyslexics was lower than the other two groups (mean = 47 hits; SD = 3.5). These results suggested that dyslexic bilingual readers can achieve good reading accuracy in Portuguese, with little or no different from controls, but this accuracy was achieved with slower reading. Dyslexic monolinguals, on the other hand, were less accurate and slower, which once more suggests that dyslexic bilinguals have an advantage in reading performance over dyslexic monolinguals. The brain activation in this task for each group showed that controls had a significant activation of left occipitotemporal and left inferior frontal gyrus while reading words. In turn, dyslexic monolinguals and bilinguals demonstrated deactivation of the left temporoparietal region and no significant activation in the left occipitotemporal region or left inferior frontal gyrus.

The neuroimaging results for the second task (FAST_LOC – Portuguese and English) showed that the dyslexic bilinguals do not present activation in the visual word form area (VWFA) for words, whereas the typical readers do. Dyslexic bilinguals have more activation for false fonts. This result showed that the VWFA has not yet automatized and adapted to the identification of the visual form of words, it is still responding more to figures. As for the Control group, activation is immediate. The results of the neural activation in the task in English and Portuguese suggested that the DDB still lack automatization in reading. These results corroborate the literature on dyslexia and how the deficit in reading is reflected in hypoactivation of areas involved with reading (Buchweitz et al., 2018; Hoeft et al., 2011; Meyler et al., 2007; Paulesu et al., 2001; Shaywitz et al., 2002).

Finally, the present study suggests that learning a second language would not hinder the reading process of individuals with developmental dyslexia, different from what was argued by Shaywitz (2008). Furthermore, it suggests that neurobiological study of the bilingual dyslexic population should be further investigated to identify the compensatory neural mechanisms that may be associated with the improvement of reading performance.

Limitations

Among the limitations of this study, we highlight the restricted number of participants recruited, which constrained the ability to generalize the findings to the broader population of individuals with dyslexia. It is important to mention that dyslexia affects between 5 and 10 percent of the population.

Proficiency in English may have posed another limitation. Participants with lower proficiency levels might have attained higher scores in English-related tasks, had they been more fluent. Nonetheless, the results put forth imply that further

investigation involving a larger cohort could provide insights into how learning a second language impacts the reading abilities of individuals with dyslexia.

Regarding confounding variables in this study, we have socioeconomic differences (DDM vs. DDB) and early bilingualism, which may not be the sole reason for the better performance of the DDB group. Concerning the first factor, although there was a significant difference in the average income of the DDB group compared to the DDM group, all participants (from both groups) attended private schools in Porto Alegre.

Finally, regarding the second confounding factor, we cannot conclusively state that early bilingualism may be the reason for the better performance of the DDB group; however, as stated before, learning an L2 did not seem to hinder the reading process of individuals with dyslexia.

Note

1. According to Seymour, Aro and Erskine (2003), the transparency of orthographies is one of the variables across languages. Orthographic transparency indicates the regularity of the letter-sound (grapheme-phoneme) associations.

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