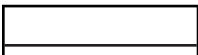# Neurophysiology of Grapheme Decoding: The N170 as A Predictive and Descriptive Tool

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ABSTRACT This study zooms in on the specialization of visual processing that underlies grapheme and word form processing, and presents an electrophysiological experiment performed with a group of 8th graders in a public state elementary school. The methodology of Event Related Brain Potential (EEG-ERP) was used to collect and analyze the N170 component, a neurophysiological signature sensitive to grapheme and word form processing. The test results indicated that, in this group, higher performance in grapheme recognition was not associated to a reduced difference between ERP wave amplitudes in response to word and false font stimuli, but instead to a clear left lateralization of print sensitive N170 responses. Differently from most ERP studies that uses the grand-averaging of all participants' ERP responses, the current analysis also investigated individual performance of participants. In this modality, the varying levels of intensity and lateralization of the neurophysiological response indicate that a large portion of the participants remain in the process of obtaining reading fluency long after having started to learn how to read. The qualitative correlation between performance and the degree of lateralization is, thus, a novel and promising measurement involving the N170 component as a descriptive and predictive tool in the monitoring of reading acquisition stages.

RESUMO Este estudo enfoca a especialização do processamento visual subjacente ao processamento de grafemas e palavras, e apresenta um experimento eletrofisiológico realizado em um grupo de alunos do 8º ano em uma escola pública estadual. Usamos a metodologia de extração de Potenciais Cerebrais Relacionados a Eventos (EEG-ERP) para coletar e analisar o componente N170, uma assinatura neurofisiológica sensível ao processamento de grafemas e palavras escritas. Os resultados indicaram que, no grupo testado, o desempenho melhor no reconhecimento de grafemas não se associa a uma diferença atenuada entre as amplitudes da onda ERP em resposta a estímulos do tipo palavra e fonte falsa, mas sim a uma nítida lateralização da resposta do N170 para o hemisfério esquerdo. Diferentemente da maioria dos estudos de ERP que trabalha só com a promediação dos ERPs de todos os participantes, a nossa análise também investigou o desempenho individual de cada participante. Nessa modalidade, os níveis variáveis de intensidade e lateralização da resposta neurofisiológica indicam que grande parte dos participantes ainda estava no processo de obter fluência de leitura muito tempo depois ter começado a aprender a ler. A correlação qualitativa entre o desempenho e o grau de lateralização é, portanto, uma medida nova e promissora envolvendo o componente

N170 como uma ferramenta descritiva e preditiva no monitoramento das etapas de aquisição de leitura.

Introduction

Reading is a cultural phenomenon that never ceases to mount in importance. In our digital world, reading takes a good length of one's daily life, and plays a pivotal role in everything from the successful mastery of essential ordinary situations, such as checking social media and completing school assignments, to psycho-social constructs such as self-reliance and the establishment and reinforcement of citizenship (FRANÇA et al., 2018).

This study zooms in on the specialization of visual processing that underlies grapheme and word form processing, and presents an electrophysiological experiment that was carried out with a group of 8th graders in a public state elementary school. The methodology of Event Related Brain Potential (EEG-ERP) was used to collect and analyze the N170 component, a neurophysiological signature sensitive to grapheme and word form processing.

Underlying a complexity of cognitive functions involved in reading, fluent access to the sounds and meanings of written words entails very fast and efficient visual recognition of letter strings. Thus, an essential building block in developing basic reading skills, in a broader sense, is the decoding of graphemes.

Unlike acquiring spoken language, learning how to read is not as easy or natural. Rather, like soccer or chess, reading is a recent cultural skill that requires considerable effort from our cognitive systems. Fully understanding which systems are involved and how they interact in order to acquire literacy is one of the hottest interests in current experimental psychology and cognitive neuroscience. Studies on that matter primarily emphasize three major brain systems, which are affected by acquiring literacy: the early visual system, the ventral visual pathway and the phonological coding system (DEHAENE et al., 2015).

When children learn how to read, their brains develop a neural network that specializes in written language. Studies have shown that this process transforms visual processing, even when literacy is acquired later on in life (COHEN et al., 2000; McCANDLISS et al. 2003; COHEN, DEHAENE, 2004; LIU et al., 2013). At the neural level, a cortical area located in the left occipito-temporal cortex, named the Visual Word Form Area (VWFA), has been recognized for processing written words (COHEN et al., 2004)

Dehaene et al. (2010) propose that the development of this specialized network can be described as 'neuronal recycling' because it invades cortical territories dedicated to other related functions and shifts their processing mode. As such, literacy acquisition may also have a negative "unlearning" effect on the visual system, distributing visual processing of other types of objects, such as instruments or faces in the areas around the VWFA (ANDRADE, FRANÇA, SAMPAIO, 2018).

Grapheme decoding is not only special due to the intimate relation with phonological and lexical processing, but also due to the specific visual characteristics of the alphabetical representation. Different forms of letters may all refer to one phonological representation, such that, for example, *mesa*, MESA and mesa, all refer to the same phonological representation of /'meza/, meaning <chair>, in Portuguese. The cognitive gymnastics of linking variant forms to one symbolic representation is a striking feature of grapheme processing. On the other hand, there is no variance allowed in other graphemic aspects; for example, b and d, mirror images of the same form, correspond to a different phonological value. With reading acquisition, familiarity of graphemic context is also a factor: it is easier to recognize a *d* embedded in the word *admirer* than it is in the ilicit sequence *dmreai*, for example (DEHAENE et al., 2010).

In fact, the proposed recycling of the VWFA may be linked to such aspects, considering that biology may have not prepared us for reading – a cultural artefact – but it has endowed us with the ability for certain particularities in visual processing. Differently from the visual recognition of, say, a flower or a house, in facial recognition, we are strongly biased for upward processing; turning faces upside down knocks out facial processing (LUCK, 2002; HAHN, JANTZEN, SYMONS, 2011). The idea of recycling, then, suggests that the VWFA does not become exclusively responsive to grapheme-like stimuli, but that it continues to respond to visual stimuli, such as faces and object, albeit, to a lesser degree.

The VWFA has also been associated with a negative ERP component. In the literature of ERPs/EEG, the specialization for reading has been characterized by the P1 – N1 components. The visual P1 is an early occipital component, with maximum amplitude at 100ms (CLARK, FAN, HILLYARD, 1995; DI RUSSO et al., 2002b). It is usually the earliest observed component, known to be sensitive to many low-level properties of visual stimuli (REGAN, 1989). The N1 component, also known as N170, is an occipito-temporal negative component, peaking at ~170ms (BENTIN et al., 1996). Traditionally recognized as a face-sensitive component, N170 shows the largest amplitude to faces at right lateral occipito-temporal electrode sites (ROSSION, JACQUES, 2008). However, the N170 has also been more recently elicited in response to written words when compared to low-level control stimuli, such as symbol strings, forms, alphanumeric symbols, shapes and dots (HASKO et al., 2013). The relatively larger amplitudes for letter strings, thus, marks print sensitivity in fluent readers. However, differently from N170 components in facial recognition, which tend to be either bilateral or right lateralized, the sensitivity to the N170 in response to grapheme type stimuli is left lateralized.

The N170 component and studies in grapheme processing

The development of a left-lateralized N170 component in response to visual word presentation shows differences when comparing different age groups, thus, accompanying the development of literacy. In a study carried out with pre-literate children, for example, there were no apparent differences in amplitudes in response to words as compared to symbols (i.e. false fonts). Pre-literate children with high familiarity with letters, on the other hand, did show slight differences (MAURER, BREM, et al., 2015). For second-graders this difference became considerably larger, with much higher amplitudes for word stimuli (MAURER et al., 2008). In fifth graders and adult expert readers the difference became more attenuated (MAUER et al., 2011; MAURER, ROSSION, McCANDLISS, 2008; MAURER et al., 2006).

The varying degree of differences in the response to word and symbol like stimuli marks the developmental path of decoding fluency: in the first stages of acquisition, word stimuli are still very salient, and thus, very differently perceived and processed from other visual types. Later on, as readers become more fluent, supposedly, the efficiency and automatization of the process yield relatively less pronounced amplitudes for word stimuli, since less cognitive effort is involved.

Not only do N170 amplitudes change along with reader development, but responses also become faster, with ~210 latencies in second graders to ~170 milliseconds for adults (SÁNCHEZ-VINCITORE et al., 2018). The changes in latencies reflect increasing speed in grapheme processing as it becomes consolidated in neural networks.

Another hallmark of developing fluency is the increasing lateralization of the process to the left hemisphere. Maurer and McCandliss (2007) explain this left lateral shifting by proposing the *Phonological Mapping Hypothesis*. In this view, increased integration of visual – grapheme and word form – information to phonological decoding processes underlies the left lateralization of the print sensitive N170. Great fluency leads to an automatic linguistically modulated response in occipito-temporal regions, reflecting engrained connections between phonologic- lexical and visually represented information, such that readers may even display left lateralized responses N170 if they are not necessarily aware they are reading (MAURER, McCANDLISS, 2007).

The print sensitive N170 component has been elicited not only with alphabetic print, but also with Japanese syllabic and logographic scripts (MAUER et al., 2008), as well as Chinese characters (ZHAO et al., 2012). Left lateralization in these scripts is also identified as marking proficiency, although in these scripts the nature of task demands may influence lateralization. It is possible that logographic scripts do not automatically engage phonological processes in the way alphabetic print does. In fact, in tasks that probe semantic aspects, for instance, N170 effects might be more bilateral, whereas experiments targeting phonological processing via script yield consistent left lateralized N170 effects (ZHAO et al., 2012). These findings do point more emphatically to the timing and distribution of the mapping of visual symbols to phonologic and lexical representations as functionally and anatomically guided rather than culturally determined.

Nonetheless, there are subtle differences in grapheme to phoneme mapping among languages conveyed by alphabetic systems. Tests performed in languages such as French, Finnish, and German, show qualitatively similar N170 responses to pseudowords

and words (MAUER et al., 2005; FEHLBAUM, 2013). Supposedly, this is a reflection of the transparency and relative predictability of grapheme-to-phoneme mappings, mostly captured in one-to-one associations (e.g. *<pato>* ('duck') maps onto ['patU]). In this sense, these languages differ from, for instance, English, which is characterized by more opaque spelling. In English spelling, sequences of graphemes often map onto one phoneme (e.g. 'dough' in which *<ough>* maps onto [o]) (ZIEGLER, GOSWAMI, 2005). This variability in the granularity of grapheme-phoneme associations is reflected in the degree of left lateralization of the N170 effect in response to pseudowords and words. In languages with more transparent grapheme-to-phoneme mapping, like Finnish, N170 effects to these types of stimuli are equally left lateralized, in contrast with English, in which N170 effects for pseudowords are less left lateralized than for words. This suggests that, visual perceptual expertise in grapheme processing does not generalize so easily to novel (pseudo) words in languages with opaque spelling systems.

To our knowledge, this is the first study exploring grapheme processing using ERP methodology with Brazilian Portuguese. Thus, our results may contribute to the understanding of how grapheme to phoneme mapping operates within the specificities of the Portuguese alphabet. We expect similar effects for the lateralization of N170 components considering that the relation between the Portuguese grapheme system, and the Brazilian Portuguese phonology it represents, is relatively stable and predictable.

On the other hand, methods for teaching reading skills may vary, and may possibly impact the degree to which written words map onto sub-lexical phonological representations. The so-called *global* method focuses on whole word form recognition, greatly relying on top-down contextual information for semantic retrieval of lexical items; whereas, *syllabic* or *phonic* methods focus on associations between sub-lexical phonological units (either syllables

or phonemes) and phonemes (FRANÇA et al., 2018). It is possible that for Brazilian students, who may have learnt reading through the global teaching method, the perceptual expertise of reading does not generalize to pseudoword processing, as grapheme recognition may not fully engage sub-lexical phonological processing. If this is the case, results may mirror those of English readers, who, due to the irregularities of their spelling system, rely comparatively more on whole word recognition.

The N170 component has been explored mainly in adults or in children prior or during the acquisition of literacy skills. In this study, we chose to focus on a different age group, namely, adolescents around the age of 13. Sánchez-Vincitore et al. (2017) studied fifth graders (mean age 11 years old), and found neurophysiological signatures that they deemed typical for high automaticity in grapheme decoding. However, the specific educational context may not be comparable. Although students in 8th grade have on average 6 years of reading experience, in Brazil, according to official school standards, acquiring basic reading skills may occur in a much larger interval, from 1st to 3rd grade (mean age range 7 to 9 years old). This may result in a large variety in reading proficiency among students in a given class; school teachers indeed confirm observing this phenomenon (FRANÇA et al., 2018). Therefore, the focus on this age group, for which data in the literature are still relatively sparse, may contribute to a more complete picture of the development of grapheme decoding skills over time, especially in the specific context of the Brazilian public educational system.

The ERP experiment: Materials and Methods

We carried out an *in loco* ERP study with 8th grade students from a state public school in order to investigate the degree of automation of grapheme and word form processing by analyzing

the N170 component. Participants saw four types of stimuli: words, pseudowords, false fonts and line drawn figures. These stimuli were presented in sequence, while participants had to detect repeated stimuli. Reaction Time (RT) and neurophysiological signals were collected.

Due to the age and reading development of the participants, we expected a difference between amplitudes in response to grapheme like stimuli (words and pseudowords) and control stimuli (false fonts and figures). Also, following the Phonological Mapping Hypothesis, we expected left lateralization of responses on occipital sites given the experience (at least 6 years) and time of reading skill development.

Moreover, we attempted to correlate behavioral data (accuracy and RT) to neurophysiological measures (EEG/ERP) such as the value of mean amplitudes on the left occipital sites in response to grapheme like stimuli at an individual level. This tentative analysis is based on reports that show positive correlations between such data in neoliterates (BOTZMANN, RÜSSELER, 2013; DEHAENE et al., 2015; PEGADO et al., 2014).

Participants

Twenty elementary school students participated in the study (13 girls) between the ages of 13yo (n=8) and 14yo (n=12). All participants were enrolled in 8th grade of the elementary public state school system. All participants are monolingual speakers of Brazilian Portuguese and, according to the information obtained from the school administration none of the participants were diagnosed with dyslexia or any other learning disability. They had no known visual or auditory deficits either. All parents or legal guardians had given permission previously, signing a consent form.

Procedure

Participants sat in a naturally lit room reserved specifically for the purpose of the study on the premises of the school. Participants were placed at a distance of 0,9m to a 19 inch screen. Head circumference was measured in order to determine which cap size (54, 56 or 58 cm) was to be used (ActiCAP, sold and developed by Brain Products). Then, forehead and mastoid regions were cleaned with alcohol. The cap was placed so that Cz was centralized on the head where the longitudinal and latitudinal lines cross. The Velcro band underneath the chin was adjusted and strapped, so the cap fits snugly, without causing discomfort to the participant. Thirty-two active electrodes were placed, primarily on the central and posterior areas on the scalp, following a 10-20 set-up (see Figure 1), with mastoid reference electrodes. A special electrolyte conductive gel was injected in the small openings on the side of the electrodes to ensure conductivity. These active electrodes have Ag/AgCl sensors, which allow for the precise measuring of impedance. Impedance was kept at a minimum, varying from 0 to 50 kOhms. The placement of electrodes was concentrated on the central and posterior regions of the scalp (see Figure 1), in accordance with the literature, which reports the that N170 effects are found on occipital sites (EBERHARD-MOSCICKA et al., 2016). Due to the fact that participants were adolescents, who might get impatient with the long duration of the preparation, 32 electrodes were chosen instead of 64, so as to reduce the time of placement.

Participants were instructed to remain as still as possible, and refrain from blinking, frowning, swallowing and shuffling as much as possible. The task was explained to participants, after which they did a short training session to get used to pace and to verify task comprehension. Participants' responses were recorded by pressing the space bar. Preparing the subject and recording the data took about 70 minutes.

Figure 1: The image on the left shows a participant in the experiment set up, with the EEG amplifier visible on the right. The image on the right represents the 10-20 electrode set up during (electrode montage from www.brainvision.com), with the gray areas highlighting the selected electrode sites. The areas marked in red indicate regions of interest (ROIs) selected for post-processing statistical analysis.
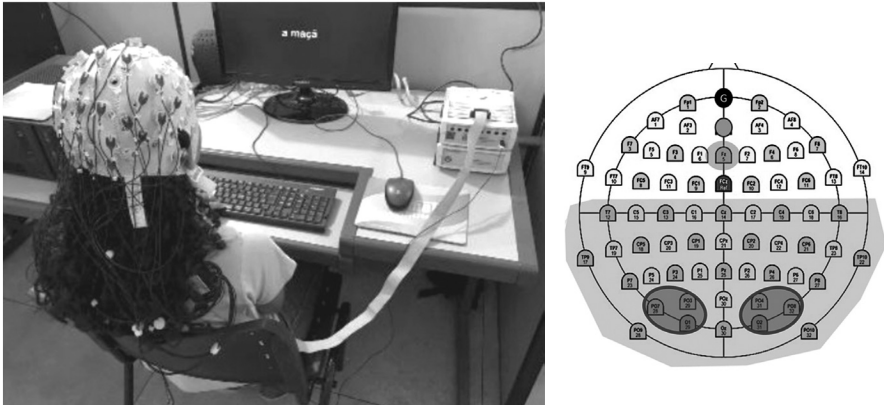
Experimental design

Materials

The independent variable was the type of visual stimulus, comparing (i) actual words in Brazilian Portuguese (e.g. *caderno* ('notebook'), to (ii) pseudowords (e.g. *basarto*), (iii) false font sequences (e.g. ¤✦⊥∧§), and line figures (see Table 1). For task purposes (repetition detection), two types of pairs were created for each stimulus type: pairs of repeated items and pairs of different items. The number of positive responses (in case of repetition) in comparison to no response (in case of no repetition) was controlled for, as well as the number of grapheme-like stimuli in proportion to other types of stimuli (figure and false font). This yielded 15 pairs of unrepeated item pairs for all stimuli types, and 15 repeated item pairs for words and pseudowords and 27 repeated item pairs for figure and false font

stimuli (see Table 1). In total, 256 stimuli were presented. These were distributed in pseudo-randomized order, and from this order two lists were produced (one list by reversing the order).

Words were controlled for the number of syllables (3), and were highly frequent words. Pseudowords, also controlled for number of syllables, were formed by adding different consonant or vowels into existing word syllable structures (ex. abelha -> **tan**elha). False font sequences were created from a script of 24 different symbols commonly found in the Microsoft Word ® 'insert symbol' section. Line figures were selected from one collection of an open access database, favoring concrete object-related images.

Table 1:   Experimental design and stimulus samples

Stimulus number and samples				
stim.type pair type	word	pseudo-word	false font	figure
repeated	caderno – caderno (*notebook*) (n=15)	basarto-basarto (n=15)	¤✢⊥∧§-¤✢⊥∧§ (n=27)	 (n=27)
unrepeated	vestido – girafa (*dress-giraffe*) (n=15)	zibelo-tanelha (n=15)	♮(₪⊨□- ✢∏○§☉ (n=15)	 (n=15)

Presentation protocol: Figure 2 shows the presentation protocol developed with *Eprime*, version 2 (Psychology Software Tools, Inc.). Stimuli were presented in white 25 pts Times New Roman font (3.5cm height or width for figures) on a black screen. The duration of stimuli presentation was 600ms, intervals between stimuli was jittered, ranging randomly from 550 to 850ms, so as to break anticipation strategies. Stimuli presentation within blocks was uninterrupted, but in between two blocks, participants could pause if necessary.

Figure 2:   Presentation protocol
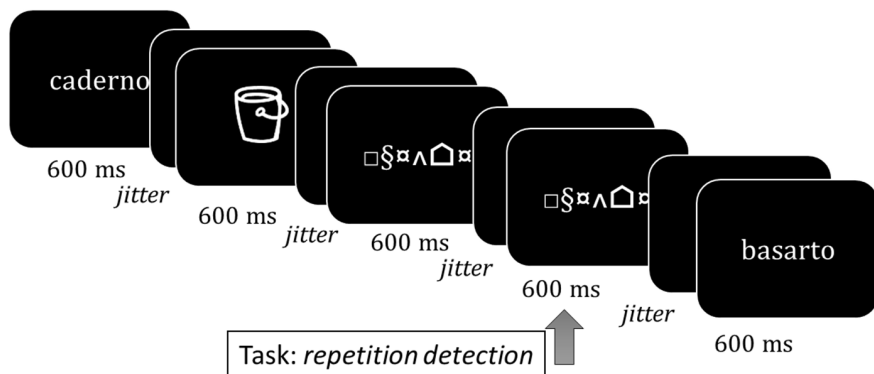
Data collection and analyses

Accuracy and duration of reaction times (RTs) were recorded by the computer on which the stimuli were presented in the E-prime software platform. Given the nature of the task, which was *repetition detection*, only correct responses could be analyzed for reaction times.

For EEG recording, ActiCHamp equipment (Brain Products) was used. This amplifier both digitalizes the EEG signals and captures triggers sent by the stimulus presentation program, allowing for the time locking of EEG signal to stimulus presentation. During acquisition the signal was filtered with a 100Hz low-pass and 0,01Hz high-pass filter. Data were digitalized at a 500Hz sample frequency by a 24-bit analog-to-digital converter.

In Analyzer (Brain Products), the continuous EEG signal was inspected for artifacts, such as eye-blinking, frowning, swallowing and other distorted signals (due to lose electrodes, cross-talking, etc.). Affected segments were eliminated. Three participant samples were eliminated due to poor signal quality, which is a relatively small loss considering the particular age group. When working with children and teens it is common to 50% of data due to collection problems (MAUER, 2005).

The remaining data were filtered with a lowpass Butterworth filter of 30Hz, corrected for DC Detrend, and segmented into epochs of 800ms, starting 200ms before and ending 600ms after trigger markers. During segmenting, baseline correction was carried out (-200 to 0ms).

Segments were averaged per condition and participant, and mean amplitude values in a 150 to 250ms (after stimulus presentation onset) interval were extracted. This interval was based on reports in N170 literature (MAUER, 2005). Based on the same reports, we focused our analysis on electrodes in the occipital region, determining two main regions of interest (ROIs): left hemisphere occipital region (O1, PO3, PO7) and right hemisphere occipital region (O2, PO4, PO6).

Only segments from same item pairs were analyzed, since priming effects for non-repeated items might vary among stimuli type (for example, even different words might engage familiarity effects that might not play any part in different items in false font pairs). The object of this study was not to investigate priming effects, but to use the repetition of items in pairs as a means to control the context in which visual stimuli appeared. Moreover, since no behavioral data were collected for different item pairs, there was no guarantee with regards to participants' attention on these trails. Therefore, we consider the investigation of these priming effects outside of the scope of this paper.

The collected data were analyzed in R (version 3.4.4), applying an ANOVA analysis. Outliers of $Z<3.00$ were eliminated from the datasets; due to this cut-off, one more sample was taken out of the EEG data sets.
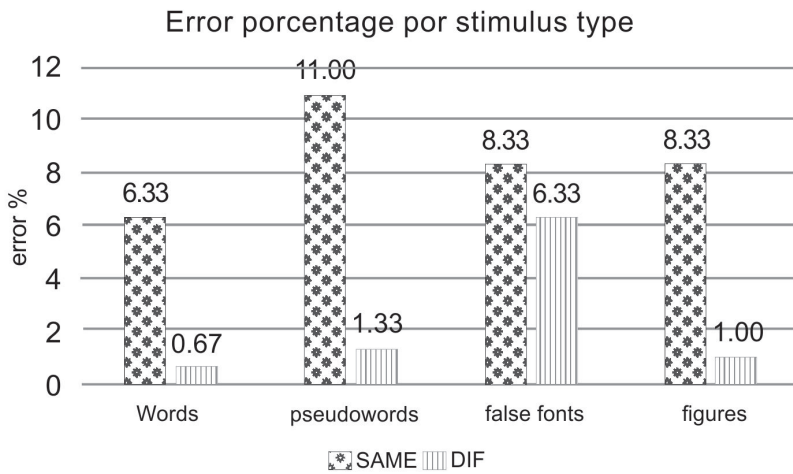
Results

Behavioral data

On average, the error percentage was 9.29% (SD:8.03%). None of the participants were eliminated due to inaccuracy, given that all participants scored well above chance. A one-way Anova analysis was applied on reaction time measures, which yielded a main effect for stimulus type: $F_{(3,1316)}=11.19$, $p<0,000$. Post hoc comparisons (Tukey) showed that the mean reaction time for pseudowords, at 536ms (SD: 143.51ms), was slower in comparison to all other stimuli types (words: 513.93ms (SD: 141.67ms); false fonts: 503.25 (SD:150.97ms); and figures: 496.88ms (SD:150.36ms) (see Graph 1). There was no statistically significant difference between the reaction times of figure, false font and word stimuli.

Graph 1:   RTs (ms) for repeated item pairs per stimulus type

Reaction Time per stimulus type
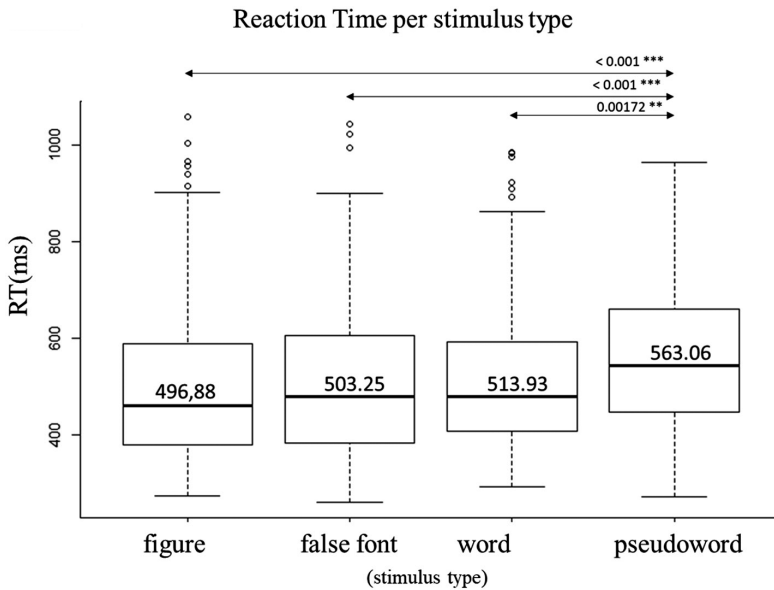
In Graph 2, we can observe a closer analysis of the error percentage per stimulus type.

Graph 2: Error percentage for same and different item pairs per stimulus type

Error porcentage por stimulus type

error %

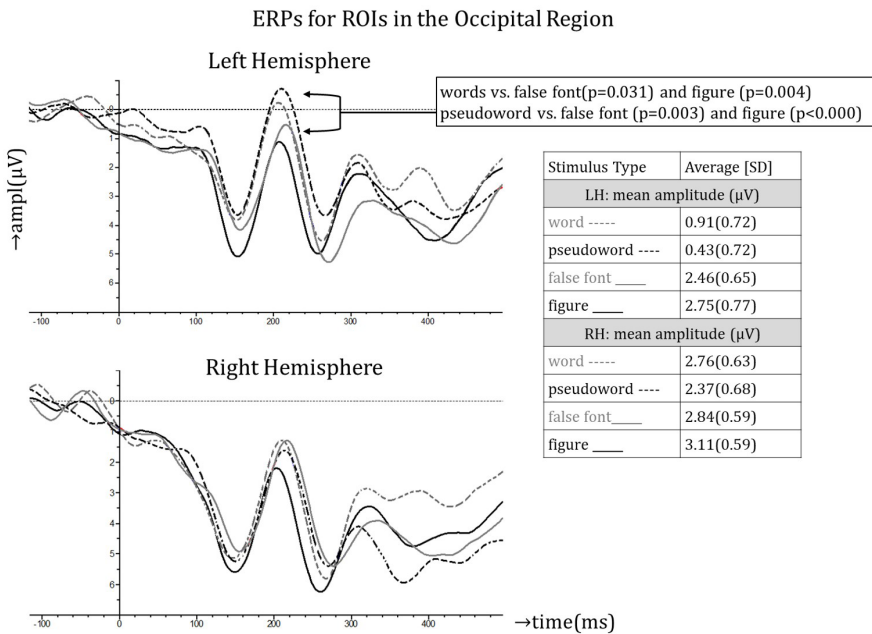|	Words	pseudowords	false fonts	figures
SAME	6.33	11.00	8.33	8.33
DIF	0.67	1.33	6.33	1.00

SAME   DIF

For words, in 6.33% of all repeated item pairs, participants failed to detect repetition. For pseudowords this percentage is nearly twice as high, at 11%, and for both false font and figure type stimuli, error rates are 6.33%. For words, pseudowords and figures, incorrect responses (i.e. pressing buttons when, in fact, items were not the same) were infrequent, with percentages of 0.67%, 1.33%, and 1.00%, respectively. For false fonts, false responses were relatively more frequent, with 6.33%. As such, the total number of false responses was highest for false font stimuli types with 14.66% in total.

Results: ERP data

In Figure 3, we present in the top graph, the ERP wave forms for the ROI on the Left Hemisphere (O1, PO3, PO7), and in the bottom graph, the ERPs for the ROI on the Right Hemisphere (O2, PO4m PO8). Mean amplitudes in the 150 to 250ms time interval were examined with a two-way Anova analysis, with two factors: stimulus type (words, pseudowords, false fonts and figures) and hemisphere (left, right). There were main effects for hemisphere ($F(1,46)=5.27$, p=0.26), and stimulus type ($F(3,138)=54.12$, p=0.003, and a marginal interaction ($F(3,138)=2.64$, p=0.052. From the ERP wave forms in Figure 3, it is clear that the combined effects for hemisphere and stimulus type is driven by higher mean amplitudes (i.e. more negative values) for words and pseudowords on the left hemisphere. Post hoc comparisons (Tukey) show that there is no significant difference between mean amplitudes for words (0.91gV(0.72gV) and pseudowords (0.43gV(0.72gV). However, amplitudes for both words and pseudowords are statistically different from amplitudes for false fonts 2.46gV (0.65 gV) and figures 2.75gV(0.77gV) (word vs. false font, p=0.031; word vs. figure, p=0.004; pseudoword vs. false font, p=0.003; pseudoword vs. figure, p<0.000). There was no significant difference between mean amplitudes for false font and figure type stimuli (word vs. pseudoword, p=0.43; false font vs. figure, p=0.65).

On the Right Hemisphere, highest mean amplitudes are for figure type stimuli (3.11gV(0.59gV), and lowest amplitudes for words (2.76gV(0.63gV), but there was no statistically relevant difference between any of the amplitudes of the four stimuli types (word vs. pseudoword, p=0.46; word vs. false font, p=0.92; word vs. figure, p=0.56; pseudoword vs. false font, p=0.53; pseudoword vs. figure, p=0.21; false font vs. figure, p=0.70).

Figure 3:   ERP wave forms for the ROI on the Left Hemisphere (O1, PO3, PO7) (on top), and for the ROI on the Right Hemisphere (O2, PO4m PO8) (below). Grey dotted lines represent responses to word stimuli, black dotted lines to pseudoword stimuli, grey lines to false font stimuli, and black lines to figure stimuli.

ERPs for ROIs in the Occipital Region

Left Hemisphere

words vs. false font(p=0.031) and figure (p=0.004)
pseudoword vs. false font (p=0.003) and figure (p<0.000)

Stimulus Type	Average [SD]
LH: mean amplitude (µV)	
word -----	0.91(0.72)
pseudoword ----	0.43(0.72)
false font _____	2.46(0.65)
figure _____	2.75(0.77)
RH: mean amplitude (µV)	
word -----	2.76(0.63)
pseudoword ----	2.37(0.68)
false font_____	2.84(0.59)
figure _____	3.11(0.59)

Right Hemisphere

→time(ms)

Discussion and Conclusions

Behavioral data

The fact that accuracy was well above chance showed that the task was relatively easy for participants; however, there were some interesting differences in responses per stimuli type. First of all, repetition detection was significantly slower for pseudowords than for all other stimuli types. We might expect this effect to be explained due to unfamiliarity for pseudoword stimuli in comparison to words, for example. In fact, we expected a priming advantage for words, as

well as figures, due to a possible familiarity effect. However, false font type stimuli are also unfamiliar, and the responses to those stimuli were also faster than RTs to pseudowords.

Therefore, rather than an effect of familiarity, we propose that participants engage in phonological coding of the pseudoword string, and subsequently, attempt to find a matching lexical representation. It is this strong integration of grapheme processing into phonological and lexical networks that triggers this highly automated process, even though the explicit task merely required the participant to recognize the visual form of the stimuli.

This 'involuntary' engagement in these processes can also be noticed in the error rate for repetition detection, which is slightly higher for pseudoword stimuli. On the other hand, it is striking that the number of times participants responded to pairs of unrepeated item within false font pairs was much higher than for any other stimuli type (6.33% vs. 1.33%, 1% and 0.67%), thus, the total of errors (6.33% + 8.33%) is highest for false font type stimuli. This result replicates earlier findings by Mauer et al. (2005), and probably relates to the relative inexperience and unfamiliarity with the visual processing of false font stimuli as compared to that of grapheme based and figure type ones.

ERP data

To our knowledge, this is the first study exploring grapheme processing using ERP methodology with Brazilian Portuguese. In many other languages, the N170 component has been explored to investigate grapheme recognition; however, mainly, in adults or in children prior or during the acquisition of literacy skills. In this sense, in terms of age group (adolescents) and language, the data are a relevant contribution to the field.

In this group of 13 and 14 year old public elementary school students, we found the neurophysiological signature that is typical of the visual specialization during the acquisition of reading. The N170 ERP component showed higher amplitudes, reflecting cognitive engagement, in response to grapheme-like stimuli (both words and pseudowords) as compared to figures and false font stimuli, on the occipital region of interest on the left hemisphere. This result is in line with prior studies, which conclude that the selective sensitivity of the N170 component to print as well as its left lateralized distribution are the hallmark of the visual specialization that comes with reading acquisition (MAUER et al., 2005; HASKO et al., 2013; ZHAO et al., 2012; GONZÁLEZ et al., 2016).

Similarly to tests performed in languages such as French, Finnish, and German, ERP responses to pseudowords and words stimuli in Portuguese were comparable in terms of timing and intensity (MAUER et al., 2005; FEHLBAUM, 2013). This suggests that the relation between the Portuguese grapheme system and the Brazilian Portuguese phonology it represents is relatively stable and predictable (MAUER et al., 2005). Specifically in our study, we found that the difference between words and pseudowords becomes more apparent in the later phases of cognitive processes. Automatic engagement of phonologic and lexical processes was reflected in slower reaction times for pseudoword stimuli, which seemed to interfere with the cognitive operations required in the task that followed mere visual recognition, such as decision making (is the stimuli repeated or not), and action planning (pressing the button), for example. This, along with left lateralized ERP responses, seems to confirm the Phonological Mapping Hypothesis, which foresees that strong connections between visual – grapheme and word form – information and phonological representations yield an automatic distribution of activation for areas engaged in visual and phonological processing in response to linguistic stimuli.

In the introduction, we suggested that there might be possible effects of the *global* reading skill teaching method on the sensitivity of the N170 to pseudowords, but we did not see any evidence of that in the group result. That is, the fact that N170 components in response to words and pseudowords were similar in intensity and distribution implies that the expertise in the visual perception of graphemes generalized to pseudoword stimuli.

Even though we found a clear group effect for stimulus type on the left hemisphere, between individuals, there was some variation in the intensity and the extent of the lateralization of the response, in combination with variations in accuracy and reaction times. Sánchez-Vincitore et al. (2017) point out that a reduced difference between amplitudes in response to grapheme like stimuli and false fonts might reflect high automaticity in grapheme decoding in fifth graders (mean age 11 years old). However, there are two reasons why we might not draw a similar conclusion in this case. First of all, although students in 8th grade supposedly have, on average, 6 years of reading experience, in Brazil, acquiring basic reading skills may occur in a much larger interval, from 1st to 3rd grade (mean age range 7 to 9 years old). Considering this variation, not all students may have equal reading experience. Moreover, when we observe accuracy scores and RT measures, it becomes clear that higher performance is not associated to a reduced difference in amplitudes in this group, but instead to a clear left lateralization of print sensitive N170 responses. We explore some of the individual data in the next section.

Individual Analyses

The potential of the N170 component as a predictive tool lies in the possibility of correlating individual performance scores and neurophysiological signatures that are either typical or atypical

for the visual specialization that underlies grapheme and word processing. If we consider that the left lateralized sensitivity of the N170 component for words and pseudowords is characteristic for specialization of grapheme specific visual processing, then we might scan individuals for typical ERP distribution patterns.

In order to test this possibility, we selected two individuals on the either end of the performance spectrum: a fast and accurate reader, and a slow and prone-to-error reader, based on the behavioral scores of the experiment. The 'strong' reader presented high accuracy scores (4.76% error rate) and fast RTs (average TR: 477.75ms); the 'weak' reader presented low accuracy scores (22.6% error rate) and slow RTs (average 737.7ms).

In Figure 3 we compare ERP responses to word and figure stimuli. On the left side, we can see ERP wave forms collected from the 'strong' reader. There are the typical neurophysiological marks of a highly grapheme sensitive response on the left hemisphere (the top graph), with a high amplitude for the ERP in response to the word type stimuli, contrasting with a low amplitude for the figure type stimuli. For the responses from the right hemisphere, we see overall lower mean amplitudes and no difference in the responses for word and figure type stimuli. On the other hand, for the 'weak' reader, presented in the graphs on the right side of Figure 3, there are no differences between amplitudes for word and figure type stimuli. Overall, amplitudes are low, except for the response to figure type stimuli on the right hemisphere

Figure 4: ERP wave forms from the occipital ROI comparing left and right hemisphere responses for words in the grey line (e.g. *caderno*; 'notebook') and figures in the black line. On the left, the graphs for the 'strong' reader, on the right, the graphs for the 'weak' reader.
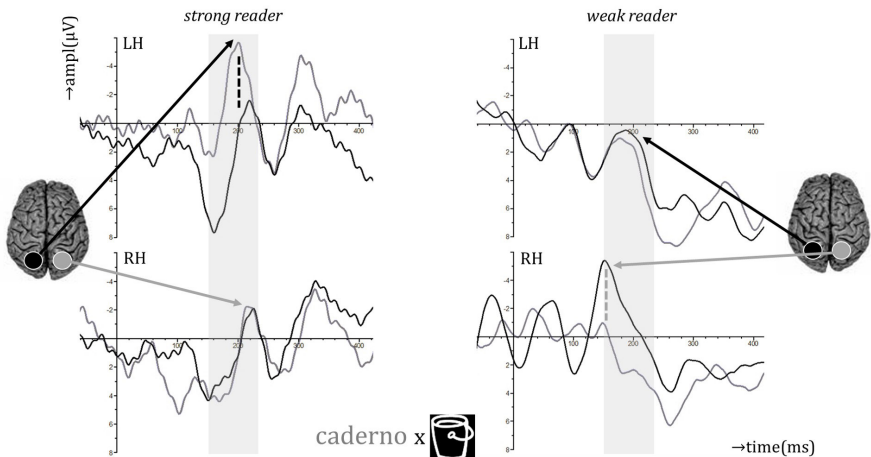
Nonetheless, when we analyze mean amplitude measures in association to behavioral scores at the group level, it is not easy to find such clear-cut correlations. There is a correlation between mean amplitude values for word stimuli on the left hemisphere and error rates (data: $t = 2.45$, $df = 14$, p=0.028) with a correlation value of 0.55. The correlation between mean amplitudes for pseudowords on the left hemisphere, and error rates are similar ($t = 2.20$, $df = 14$, p= 0.045; correlation 0.51). This reflects that, overall, strong responses on the left hemisphere to graphemes correlate with lower error rates. However, the correlation is not very strong, and, most likely requires a larger participant group, yielding more ERP data, and also a more sophisticated and robust way of testing grapheme and phoneme sensitivity in an offline test. It does, however, hint at the fact that lower error rates might be correlated to those readers that take advantage

of the relative transparency of the Portuguese spelling system, such that the ability to easily map from grapheme to phoneme in words generates to the visual processing of pseudoword. This is, of course, a useful tool when students go from reading frequent words to more infrequent words as the complexity of the texts and their subject matter increases throughout the development of their reading skills.

Indeed, the varying levels of intensity and lateralization of the neurophysiological response indicate that a large portion of the participants remain in the process of obtaining reading fluency long after having started to learn how to read. Whether the individual differences in the specific context of this group of students are the result of idiosyncratic factors, such as individual aptitude or motivation, or group factors, such as time and frequency of practice in the classroom, or, such as suggested earlier, the outcome of a specific teaching method remains a matter of speculation at this moment. Nonetheless, these are questions to be addressed by future research, for which the method applied in this study seems appropriate. The qualitative correlation between performance and, especially, the degree of lateralization are novel and promising measurements involving the N170 component as a descriptive and predictive tool in the monitoring of reading acquisition stages.

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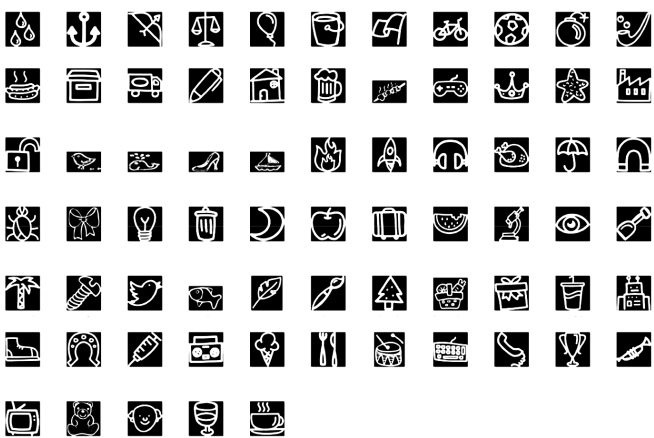
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Apendix

Stimulus list

words	words (translation)	pseudowords	false fonts
abelha	bee	aldure	(+⊙¤ℵ
arquivo	document	alnotor	(△╞¤צ
assento	seat	astreli	/Δ◈△□
banana	banana	atugar	╞∨¤צ╫
besouro	beetle	basarto	╞¤צ╫(
boneca	doll	bomeira	¤/∧△צ◈
buzina	horn	celeita	¤○○⊥∧
cabrito	little goat	colhazão	¤✛⊥∧§
cadeira	chair	colhimo	ℵ∧§⊙¤
caderno	notebook	cotila	ℵ◈○∧§¤
castelo	castle	desoico	∧§¤✛ℵ◈
coleira	collar	desouro	∧§⊙✛ℵ
espuma	foam	dozame	∧⊙¤✛∧
família	family	dubara	△╞¤צ(
farinha	flour	ebicaxo	△□ɗΔ/
gaiola	cage	elfaci	⊳ɗ/Δ✛
girafa	giraffe	enubus	⊥\╞△△צ
iguana	iguana	eslata	§⊙¤✛ℵ
jacaré	alligator	flangem	ɗ⊳Δ⊙╫
limpeza	cleaning	gabema	□∧△¤§
mercado	market	ganeza	□ɗ/Δ◈
morango	strawberry	gavito	צ(╫△╞
número	number	genora	צ□ɗ╫(△
orelha	ear	jafope	צ╫(△╞
ovelha	sheep	joilom	╫(ℵ╞¤
palácio	palace	mácido	╫╞⊳Γ✛
palavra	word	matalão	✛ℵ∧§⊙

palhaço	clown	miloura	✢▷◈Γ
piloto	pilot	nemino	✢▷Γ⊡⊙
rainha	queen	petrudo	✢§□Γ⌂
recreio	playtime	pinduta	✢Л⊖§⊙
sorvete	ice cream	raelha	⊙§Γ+⊡
tomate	tomato	someba	⊙♂Δ ♮Л
varanda	balcony	talezo	⊙✢▷◈Γ
vestido	dress	tanelha	⊙Δ♂Л♮
		tapelo	⊙Δ✢▷◈
		zalate	⊙ΔΔ✢⚵
		zanilho	Л◈§¤∧⊡
Figures:		zibelo	Γ⊡⊙✢
			Γ⊡⊙✢▷
			Γ+⊡⊙
			Γ⌂✢⚵⊙/
			Γ✢♮⟝▷
			Γ⊙Ọ/◈⌂
			Δ\⌂⊙Δ
			Δ◯/◈⌂
			Δ◈⌂□♂
			Δ✢▷◈⊙
			¤⚵♮(⌂