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Analysis of Pseudohomophone Orthographic Errors through Functional Magnetic Resonance Imaging (fMRI)

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Reading is a cognitive process that requires the visual identification of written elements and their respective phonological association to form meaning. Reading involves activating the participation of several brain regions; mainly cortical, thus forming what some authors have called a specialized system for reading (Berninger and Richards, 2002).

The reading system can be divided into three main anatomic regions: occipital-temporal, temporal-parietal, and inferior frontal. The first one, where the fusiform and lingual gyri stand out, has been linked to the orthographic analysis of words. Activations have been reported in the left hemisphere's fusiform gyrus when faced with words in tasks requiring relatively simple manipulation or processing, such as visual priming (Glezer et al., 2009), lexical decision (Cohen et al., 2002), or decision on the morphological structure of words (Binder et al., 2006; Kronbichler et al., 2008). This region has been called the Visual Word Form Area or VWFA, also called occipito-temporal or OT area (Cohen et al., 2000). Nevertheless, this area is also activated by perception and naming visual objects and in the processing of several other kinds of stimuli, and therefore its specialization in reading has been questioned (Price and Devlin, 2003).

The temporal-parietal region, mainly Wernicke's area, the angular gyrus, and the supramarginal gyrus, has been linked to the phonological decomposition of words and the onset of their semantic processing (Simos et al., 2002).

Activations have been found in the upper portion of this area, particularly in the posterior region of the superior temporal gyrus during phonological processing tasks (Burton et al., 2000). Finally, the inferior frontal region, Broca's area, and the inferior frontal gyrus, as well as the insula, have been linked to the phonological processing of words (Borowsky et al., 2006). The inferior frontal gyrus has been divided into two distinct regions: the pars triangularis, and the pars opercularis. The first one has been linked to semantic processing, and the second one has classically been linked to phonological processing (Bockheimer, 2002). Inferior frontal gyrus activations have been reported in tasks requiring word information processing in relation to their meaning, such as semantic categorization (Hirshorn and Thompson-Schill, 2006), and also in tasks requiring phonological processing, such as silent reading (Pugh et al., 1997).

Orthographic codification can be defined as a unique arrangement of letters that defines a written word, as well as other general aspects of writing such as the dependencies in the word sequence or the letter position (Tanzman,1984, cited in Castles and Nation, 2006). In accordance with Perfetti (1992), skilled processing implies acquiring fully specialized orthographic representations so that the context is unnecessary to recognize specific words. It is a highly automatized process and cannot be consciously subjected to strategic control. These characteristics allow the reader to provide more attentional resources to other reading aspects such as text significance (Ehri, 1995). Just as posterior occipital-temporal brain areas are related to a first level of orthographic processing, the long-term orthographic representations are related to bilateral inferior frontal brain areas (Richards et al., 2006). The work by Richards et al. (2006) suggests that normal children showed significantly greater right inferior frontal gyrus activations in orthographic processing tasks and the activations of dyslexic children in this area tend to normalize after orthographic treatment. The work by Booth et al. (2007) showed that, in a task in which the participants had to decide if two spoken words had the same spelling for the rhyme, the conditions with conflicting phonology and orthography were associated with greater activation in the left inferior frontal gyrus (Booth et al., 2007). The work by Richards et al. (2009) suggests that good spellers activated the left inferior frontal gyrus more than the poor writers in a task where the subjects had to decide if both words in different pairs of words were both correctly spelled. The results of Edwards et al. (2005) suggests that the processing of pseudohomophone words largely activated the bilateral inferior frontal gyri, when compared to the tasks in which the subjects were asked to process consonant strings or pseudowords. In the work by Newman and Johanisse (2011), in which the participants were asked to perform several lexical decision tasks, the authors manipulated the possible reliance on orthography by varying the degree on which non-word stimuli were more or less orthographically typical. Their results suggested that pseudohomophones in the word-like context produced greater activations relating to non-words in the left inferior frontal gyrus, among other areas.

The majority of the studies previously mentioned have been conducted on deep orthographies. Orthographic consistency and its corresponding instructional regime could lead to the adoption of different reading strategies across languages based on visual or whole word recognition in deep orthographies and on phonological recognition in shallow ones (Wimmer et al., 2010). Spanish, like Dutch, Italian and German, is considered a language with a regular orthography, thanks to their regular orthography, children can easily acquire phonological recoding strategies given the high feed-forward consistency between spelling and phonology (Ziegler and Goswami, 2006). However, in the case of standard Spanish, some phonemes could be mapped onto two or three different letters, and in Mexican Spanish, other additional sounds are also equivalent. For example, the phoneme /s/ matches the graphemes “c”, “s” and “z”; the phoneme /x/ matches the graphemes “x”, “g” and “j”; the phoneme /j/ matches “y” and “ll”; and the phoneme /b/ matches “b” and “v”. Therefore, in Spanish it is relatively common to write pseudohomophones (words with an orthographic error but with the same phonology as the correct one) or to recognize a pseudohomophone as a valid word during reading. For example *cilantro* –coriander– is correctly spelled with a “c”, but the general population frequently accepts pseudohomophones such as silantro and zilantro as valid words. Although these mistakes do not significantly compromise reading comprehension in normal persons, they do cause the speakers of Mexican Spanish, to make numerous pseudohomophone spelling mistakes, something observable in the general population (Gómez-Velázquez et al., 2014). In fact, in this same study, it was observed that the low spelling skills (LSS) group make three to four times more orthographic errors than the high spelling skills (HSS) group, but both groups present normal reading speed and comprehension indexes (Gómez-Velázquez et al., 2014).

The brain processing of pseudohomophones has been relatively poorly studied. The main objective of the present study was to explore the possible differences in behavior and in brain area activation patterns during the processing of pseudohomophone errors in two groups of people. Both groups were comprised of normal readers, but one presented high spelling skills (HSS) and the other low spelling skills (LSS) because, as we have said, great differences exist in the Mexican population in orthographic recognition between normal readers. We have proposed to study orthographic recognition by means of an explicit and an implicit task. This type of paradigm, which is related to concrete cognitive processing, has been used in other reading-related studies (Brunswick et al., 1999).

Accordingly, our main hypothesis is that HSS people would be more efficient when they pay explicit attention to orthographic errors than the LSS people. However, for implicit orthographic recognition, the performance of HSS people would be worse than that of LSS people, because HSS makes two tasks the recognition of a letter and the detection of orthographic error and the LSS only makes the letter-searching task. This is because HSS people have automatized the recognition of orthographic errors and this automation interferes with a new task in which people only need to recognize whether a letter is present independently from whether the word is spelled correctly or not, an effect similar to the Stroop effect. This effect has been expressed as the existence of a “reader instinct” (Paulesu et al., 2010).

For brain activation, according to Edwards et al. (2005), Richards et al. (2006), and Booth et al. (2007), we hypothesize that the detection of orthographic errors will activate bilateral inferior frontal gyri, and that this effect will be greater in the HSS group. According to our second behavioral hypothesis, HSS people will show similar activations in the implicit and in the explicit task because HSS participants will tend to conduct an involuntary orthographic recognition during the implicit task, while LSS people will not show activation in inferior frontal gyri since their poor orthographic automated skills will impede to conduct involuntary orthographic recognition when they were focused on a letter-searching task.

Method

Participants

Twenty-four young adults (M=21.83 years, SD=5.02, 10 women) participated in the experiment. They were all right-handed, in accordance with the Edinburgh Handedness Inventory (Oldfield, 1971), with normal or corrected vision and no history of neurological illness or learning disorder. They all signed an informed consent and received economic compensation for their participation, in accordance with the permission and recommendations of the Ethical Committee of the *Instituto de Neurociencias* of the University of Guadalajara, Mexico. They were assigned to two groups (High Spelling Skills – HSS, or Low Spelling Skills – LSS) according to their performance on five tasks that assessed their orthographic knowledge, particularly the use of pseudohomophone spelling in words (b-v, c-s-z, g-j, ll-y, h-*no* h). These tasks involved pseudohomophone spellings, dictation of a letter, dictation of a list of words, detection of pseudohomophone errors in a text, and a free-topic essay. The tasks were applied to all participants *prior to* the neuroimaging registration to discriminate the participants' performances. In a previous study, these tasks had presented an adequate reliability value ($\alpha = .833$) and a very high discriminability capability to distinguish between groups with different orthographic abilities (t = 11.608; p< 0.001) in a sample of 827 young adults (Gómez-Velázquez et al., 2014). To be assigned to the HSS or LSS groups, we considered the 15th and 85th percentiles of the total number of errors across all tasks (7 or less, and 31 or more, respectively).

A reading performance test was also applied *prior to* the neuroimaging studies. It involved reading a 154-word text aloud. The participants were asked to read as fast and accurately as possible and told that they would be asked about the task at the end. Finally, five questions related to the text were scored with 2, 1, and 0 points for complete comprehension, partial comprehension, and misinformation or lack of response, respectively.

Stimuli and procedure

Two experimental tasks were applied in which the participants were exposed to 60 words spelled correctly in Spanish and to 20 words with a pseudohomophone orthographic error (for example, '*sapato*', whose correct spelling is *"zapato"* -shoe-). In the first task (blocks A and B, spelling recognition task), the participants were required to indicate whether the word was spelled correctly or else contained a pseudohomophone orthographic error. In block A, 50% of the words were spelled correctly and the remaining 50% contained an orthographic error. In block B, 100% of the words were spelled correctly. In the second task (blocks C and D, letter-searching task) the participants were instructed to answer whether the word presented contained the vowel "i" or not. In block C, 50% of the words were spelled correctly and 50% contained a pseudohomophone orthographic error. In block D, 100% of the words were spelled correctly. Both the stimuli and the interval between them were 1 second long. Both tasks were counterbalanced across all participants. To present them, a block design was used: the stimuli were divided into 8 blocks with 10 stimuli into the blocks and presented pseudo-randomly. The stimuli were presented in white on a black background, with an Arial 60 font and a 300-pixel-per-inch resolution. To control the speed of recognition of very frequent words, the list of stimuli was balanced by using frequent and infrequent words according to the Computerized Lexicon of Spanish, LEXESP (Sebastián et al., 2000) and a frequency dictionary designed at our laboratory. The stimuli were presented using E-Prime software (Shneider et al., 2002) through an MR-safe goggle system. The list of stimuli used in this research may be consulted in appendix A.

Image acquisition

GE Excite HDxT 1.5 Tesla equipment (GE Medical Systems, Milwaukee, WI) and an 8-channel head coil were used. For each experimental task, 32 4-millimeter-thick (mm) contiguous axial slices were obtained. An echo planar pulse sequence was used with a repetition time of 3 seconds, echo time of 60 milliseconds, 26-centimeter FOV, and a 64 x 64 matrix. The voxel size used was 4.06 x 4.06 x 4 mm. From each experimental task, a total of 62 brain volumes were obtained. For reasons of image acquisition time and experimental design, 6 brain volumes per task were discarded (the two first volumes dedicated to a resting state, and four volumes dedicated to advising the experimental procedure initiation), thus leaving a total of 56 for later analysis (Figure 1).

Figure 1. Experimental design. Rest (R) and activation blocks A and B for the spelling recognition task, and C and D for the letter-searching task. The first two brain volumes were eliminated from the analysis, as well as the four task warning volumes. '*Maíz*' (corn), '*hijo*' (son) and '*riqueza*' (wealth) are examples of correctly spelled words. '*Consepto*' (concept) is an example of an incorrectly spelled word (pseudohomophone), with an *s* instead of a *c*, thus generating a pseudohomophone error.

The pre-processing and the statistical analysis of the images were conducted by means of the SPM8 computer package (http://www.fil.ion.ucl.ac.uk/spm/software/spm8/). The images were spatially realigned, readjusted to the voxel size, and normalized according to the MNI reference – *Montreal Neurological Institute* – and Talairach coordinates. For the smoothening, a Kernel *Gaussian* filter three times the voxel size was used on the x, y, z axes, following the recommendations of the SPM preprocessing procedure and in agreement with the results of Farràs et al. (2015). Based on the analysis of each group in each task, regions of interest were formed by means of the MarsBar software.

Results

Orthographic and reading performances

As mentioned above, we took the 15th and 85th percentiles of total errors in the orthographic tasks as cut-off points to form the HSS group (M = 4.42, SD=2.11, range=1-7) and LSS group (M = 42.58, SD=9.99, range=32-63).

A significant difference in reading speed was found between the groups (t (22) = 4.24, p< .001, r = .671), with a greater number of words per minute in the HSS group (M = 161.39, SD=17.70) than in the LSS group (M = 135.42, SD=11.73). Furthermore, when we considered modifications and omissions, there was a statistically significant difference between both groups (t (22) = 3.22, p< .01, r = .566), with fewer errors observed in the HSS group (M = 3, SD=2.30) than in the LSS group (M = 7.25, SD=3.96). Despite the differences observed in reading speed and accuracy, no differences were observed between the groups regarding comprehension (t (22) = 0.52, p = .61), although answers from the HSS group (M = 8.08, SD=1.31) were slightly more adequate than those from the LSS group (M = 7.75, SD=1.77).

Behavioral

The behavioral results from the experimental tasks were analyzed to compare the performance between the groups. To that end, several univariate covariance analyses (ANCOVA) were conducted for each dependent variable (number of correct answers and reaction time for each overall response) in relation to i) a comparison of the AB blocks, ii) a comparison of the CB blocks, and finally iii) the effect of tasks and blocks. The participant's age was used as a covariate to extract the components caused by that factor. For each analysis, we carried out a factorial design involving orthographic competence (High or Low) as a between-groups factor, while the within-groups factor was the cognitive domain involved in the paired task (spelling recognition or letter-searching for the two first analyses).For the third analysis, two within-groups factors were used: the task (spelling recognition and letter-searching) and the different blocks of percentage of words spelled correctly (50% or 100%). We saved the third analysis to clarify the general effect between conditions. Table 1 shows the relevant statistics and the significance values of raw data for the number of correct responses in each task (detecting the existence of a pseudohomophone error in the spelling task, and detecting the existence of the *i* vowel in the letter-searching task) and the reaction time for all of the correct responses (yes or no depending on the stimulus). The complete contrast was analyzed according to $\alpha = .001$ after applying Bonferroni correction.

PLEASE INSERT TABLE 1 HERE

For the spelling task (AB), which involved the number of correct answers, only the group effect was statistically significant ($F(1,21) = 52.72$, $p<.001$, $\eta^2 = .715$) as well as the first order interaction Blocks x Group ($F(1,21) = 15.64$, $p=.001$, $\eta^2 = .427$). The HSS group had better results in the A blocks than in the B blocks, whereas the effect was the opposite for the LSS group, but the performance of the HSS is always better than the performance of the LSS. Regarding the reaction time, no source of variation was statistically significant.

In the second analysis, the letter-searching task (CD), regarding the number of correct answers, we found a statistically significant effect for the interaction Blocks x Group ($F(1,21) = 15.35$, $p=.001$, $\eta^2 = .422$). Therefore the HSS group presented a better performance in the D blocks while the LSS showed a better performance in the C blocks, and in the two blocs the performance of the LSS group is always better than the performance of the HSS group. As for reaction time, the interaction Blocks x Group was also statistically significant ($F(1,21) = 13.71$, $p=.001$, $\eta^2 = .395$); in the C block, the LSS group was faster than the HSS group, but this effect is contrary to the effect in the D block.

In the third analysis, we included the task (spelling and letter-searching) and the block (50% correctly spelled stimulus and 100% correctly spelled stimulus) as within-group factors, and the group (HSS and LSS) as a between-groups factor, so we conducted a mixed factorial analysis (2x2x2). As regards the number of correct answers, four of the sources of variation were statistically significant, including the effect associated with the covariable age ($F(1,21) = 2.07$, $p<.001$, $\eta^2 = .762$), and the effect associated with the group, ($F(1,21) = 23.31$, $p<.001$, $\eta^2 = .526$); in this case, the number of correct responses was higher in the HSS group than in the LSS group. However, the most interesting sources of variation were those related to the interaction Tasks x Group ($F(1,21) = 60.03$, $p<.001$, $\eta^2 = .741$) and Tasks x Blocks x Group ($F(1,21) = 27.17$, $p<.001$, $\eta^2 = .564$). Regarding the spelling task, the number of correct responses was higher in the HSS group than in the LSS, but this difference was lower in the B block. Conversely, for the letter-searching task, the number of correct responses was higher in the LSS group than in the HSS group. Regarding the reaction time, no source of variation was statistically significant. A simple way to observe the complexity of interaction effects in both dependent variables can be seen in Figure 2.

Figure 2. Effects on the number of correct answers and the reaction time according to the high (HSS) and low (LSS) spelling skills groups and their interaction with the type of task and block.

Neuroimaging

Based on the linear models of the SPM algorithm, we carried out a mixed factor ANOVA separately for each group with specific contrasts as follows: A> B, C > D, A > C and B > D. Greater region activation was observed in the LSS group when deciding on the word's orthographic structure in the spelling recognition task. These activations appeared bilaterally, especially in two great groupings located in the inferior temporal gyrus, with a greater predominance towards the right hemisphere, and in the middle temporal gyrus, in the right hemisphere predominantly. Additionally, activations were also observed in this group in the right hemisphere's supramarginal gyrus and in the middle portion of the frontal gyrus. Likewise, this group presented activation in subcortical regions such as the cerebellum, the parahippocampal gyrus, and the anterior cingulate region, all of them in the left hemisphere. In contrast, the group analysis of the HSS group revealed the activation of a small grouping located in the right hemisphere's pre-central gyrus. The exact location of the aforementioned activations can be seen in Table 2 and graphically in Figure 3.

PLEASE INSERT TABLE 2 HERE

Figure 3. Statistical significance maps by regions for the spelling recognition task (A and B blocks) in the high (HSS, red-yellow) and low (LSS, blue-green) spelling skills groups.

When the participants had to decide on the presence of one letter in the words in the letter-searching task, independently from the spelling of the words, the analysis of both groups showed similar activations in the pre-central frontal gyri. Only the HSS group presented bilateral activations in the former region; regarding the latter region, the activations of the LSS group were anatomically inferior with respect to the other group. The activations in this task can be seen in Figure 4 and table 2.

Figure 4. Statistical significance maps by regions for the letter-searching task (C and D blocks) in the high (HSS, red-yellow) and low (LSS, blue-green) spelling skills groups.

The comparison of both groups between both tasks revealed an activation of the HSS group in the region of the right hemisphere's middle frontal gyrus. Task comparisons showed an activation of the left hemisphere's post-central gyrus, as well as bilateral activations of the superior temporal gyrus. Group interactions by task revealed activations in the posterior portion of the middle temporal gyrus and in the parahippocampal gyrus (Figure 5 and Table 3).

Figure 5. Statistical significance maps by regions based on the ANOVA analysis groups by tasks (blue to red show the statistical intensity effects).

PLEASE INSERT TABLE 3 HERE

To establish the impact of the experimental conditions on the brain signal analyzed, we studied the values of the parameters from the general linear model (GLM) estimated from the solutions by means of ordinary least square (OLS) of the contrasts defined for each experimental condition. In addition to the general analysis established on the second level defined on SPM8, it was deemed necessary to study the distribution of the estimates of the parameters associated with each contrast in each of the participants in each experimental group. In this manner, we used the βi values linked to the effect of the experimental conditions, and we analyzed the parameters for each contrast and participant by means of a mixed ANOVA of repeated measures, thus defining the competence levels as an inter-group effect, with the different contrasts analyzed as an intra-group effect. To avoid the possible "double dipping" effect described by Kriegeskorte et al. (2009), all ANOVA contrasts were conducted using orthogonal coefficients so that effects were not overestimated. Likewise, the significances of this phase were carried out under the criteria of false discovery rate (FDR = .0001). Table 4 shows the significance values of the usual descriptive parameters and statistics.

PLEASE INSERT TABLE 4 HERE

Based on this analysis, we were able to observe that the impact on the AB, AC, and BD contrasts was greater for the participants in the HSS group, exactly as in the case of the CD contrast, which was less intense. Obviously, the last contrast, ABCD, is of less interest because it is a comparison between non-strictly analogous tasks. It seems clear that the spelling recognition task (A and B blocks) caused a greater impact on the HSS group ($F(3,22) = 12.44$, $p < .001$, $\eta^2 = .432$) than on the LSS group, whereas the same was true for the letter-searching task (C and D blocks) ($F(3,22) = 7.12$, $p = .037$, $\eta^2 = .197$), with a p value less significant than in the other contrast, but also statistically significant.

Discussion

According to the results from the spelling recognition task, the LSS group showed poorer behavioral performance (fewer correct responses and higher reaction times) compared to the HSS group. When the participant's attention is focused on the orthographic structure of the words (spelling task blocks AB), the group with high skills (HSS) was faster and more accurate than the group with low skills (LSS), an expected result because the groups were formed according to this skill. However, when the participants had to detect the presence of a letter in the words (letter-searching task blocks CD); the answer pattern was the opposite. It is important to note that, in both tasks, we presented words spelled correctly and incorrectly. We believe that the group with high skills, which we consider to have reached an automation of the orthographic word structure, conducts two tasks in blocks CD: identification of the letter in the presented stimulus (instruction done in these blocks) and an orthographic analysis (automation process). Meanwhile the group with poorer orthographic skills only conducts the task regarding the instructions, the identification of a letter.

In our work, in the spelling task, the HSS group basically showed activations in the right inferior frontal regions. Some studies have related these regions with some aspects of the long term orthographic processing. In the work of Eckert et al. (2003), the size of this structure was positively correlated with behavioral spelling measures. In other studies, healthy children showed more activation in right inferior frontal and right posterior parietal areas during orthographic mapping, and the activations in the same areas in dyslexic children increased and were normalized after an orthographic treatment (Richards et al., 2006). In addition the same study showed that normal and dyslexic people present different connectivity patterns in the inferior frontal gyrus and the visual Word Form Area. Also, the work by Edwards et al. (2005) suggests that the processing of pseudohomophone words largely activated the bilateral inferior frontal gyri when compared to the tasks in which the subjects were asked to process consonant strings or pseudowords. Taken together, these studies are in line with the results of our work because they suggest an implication of right frontal regions in long term orthographic processing. However, Richards et al. (2009) selected good spellers and bad spellers from a normal reading skills group of children, and they found more activation in the left inferior frontal for the good spellers than for the bad spellers. Other works also showed that the discrimination between pseudohomophones and words spelled correctly activates left frontal inferior regions (Booth et al., 2007). Nevertheless the latter work also supports our results partially, as these authors found that a better performance in their task correlated with higher activations in the left inferior frontal gyrus in the situations with greater orthographic-phonological conflict. This result is, to some extent, similar to that obtained in the HSS group, because in the AB pair, in the A condition, 50% of the words were spelled correctly and, therefore, a more difficult task associated with greater activations in the inferior frontal gyrus in the HSS group. In addition, other authors show that there is an important functional connectivity between both homologous regions (Richards et al., 2009), so it is possible that both right and left inferior frontal areas are involved in some way in the long term orthographic representation. Because the long term orthographic knowledge comes from multiple linguistic sources, for these authors, the left inferior frontal areas act as orthographic central executors, regulating the activity of multiple posterior brain areas that contribute to long term orthographic knowledge (Booth et al., 2007; Richards et al., 2006). The latter idea is also supported – to some extent –by the results obtained by the LSS group because if long term orthographic recognition has multiple linguistic origins (Richards et al., 2006), it is plausible that, in the absence of frontal inferior control, our participants show weak activations in multiple posterior brain areas when they try to detect orthographic errors. Not only did LSS participants show a different activation pattern than the HSS participants, but these activations were also significantly weaker.

These uncoordinated activation patterns for the orthographic detection task in the LSS group are in accordance with their behavioral performance –which is poorer – so it might be a link between the loss of inferior frontal activation and the inability to perform at the task. The fact that, in our study, we only obtained activations in the right inferior frontal gyrus and not bilateral may be due, in addition, to the fact that Spanish is a transparent language and therefore with a high feed-forward consistency between spelling and phonology. We should add to this the fact that the pseudohomophone stimuli used in our study only differ from the correctly spelled word in one letter which is in the same position where the correct letter would be and, as we mentioned in the introduction, these pseudohomophones are often accepted as a correct word. Accordingly, the participation of the left inferior frontal gyrus in the phonological and semantic processing of our stimuli would be practically the same in blocks A and B, and the activations observed during this pair of tasks in the right inferior frontal gyrus might be due to aspects of working memory and executive control of orthographic processing. Nevertheless, we must be cautious with this interpretation of the data given that our design does not allow us to study the involvement of these processes in the recognition of pseudohomophone errors directly.

Our results are also compatible with those of González-Garrido et al. (2014), who suggest that the electrophysiological correlates of orthographic errors processing have shown that adults with low orthographic abilities have problems in detecting orthographic rule violations, which could indicate weak representations in the orthographic lexicon or a difficulty in automatically accessing such representations.

Accordingly, when the participants had to decide on the presence of a visual trait of the word (identification of one letter in the letter-searching task), apart from the orthographic structure, the HSS group yielded a significantly smaller number of correct responses than the LSS group in the block where orthographic errors were presented (block C). In this block, HSS participants show partial frontal activation, which they presented for the orthographic recognition task (AB), and activations in the medial frontal gyrus. This activation pattern, which is in some aspects compatible with the pattern observed for the spelling task, jointly with the behavioral pattern, suggests that these participants in the CD blocks conduct the orthographic recognition task and the letter-searching task at the same time. Some studies suggest that the HSS group can automatically recruit posterior brain areas related to the orthographic processing even in a task which does not require them to (Cone et al., 2008). Hence, it is plausible to think that HSS participants conduct both tasks in the second task (CD) after being exposed to the first task (AB). On the other hand, interpreting our results in this light complicates interpretation of the activation pattern found greatly because the HSS participants performed two different orthographic tasks while alternating their attention between the two tasks. Accordingly, the brain activation pattern obtained could be partly related to the high cognitive load of this condition.

The idea that HSS participants automatically conduct the orthographic error detection task is reinforced by the fact that the LSS participants only presented activations in the left pre-central gyrus and in the right superior frontal gyrus, and these activations were smaller than the same ones presented in the HSS participants.

Our study presents some limitations that should be noted. The most important one refers to the letter-searching task. In block C, the cognitive load and the set of tasks that the participants must conduct make it difficult to interpret the activations in this task in a meaningful anatomical way. Likewise, it is difficult to interpret the interaction effects group by task, where the HSS participants showed temporal activations and the LSS participants showed hippocampal activations. It is possible that a combination of our spelling task with the task implying the reading of pseudowords could provide a wider perspective about the relationship between brain activations and orthographic knowledge.

Another limitation of our study is the sample size we selected, which may be considered rather small. However, this should be seen as a relative limitation. The criteria to confirm the groups were strict, and the method of assignment to the groups, following the extreme values criteria, allowed us to maximize the possible differences. This made data interpretation rather clear in terms of brain activation despite the relatively small sample size (Friston, 2012; Logothetis, 2002). Apart from the sample size, the regularity of the effects and the activations found in the intra-group effects guarantee the homogeneity of the sampling and the correct application of the experimental procedure.

Yet another limitation of our paper might be the choice of a block design instead of an event-related design. However, the manner in which the blocks and the stimuli between blocks were manipulated allowed us to conduct the study adequately. First, it should be understood that the participants carried out block A task first, where only 50% of the words are spelled correctly. This manipulates the participant's expectations deliberately so that in block B they do conduct the spelling assessment. While preparing the experiment, we realized that the brevity of the blocks, their order, and the global duration of the experiment prevent the participants from automating the answer "YES" in blocks "B" and causes them to stop processing the information. The fact that we deliberately manipulated the participants' expectations with block A allowed us to conduct a design that makes it possible to make reasonable predictions regarding the results and that fits perfectly into a block design. In turn, that allowed us to conduct an experiment with relatively few words, thus facilitating the control of word frequency between blocks. It should be noted that this precaution is essential if we keep in mind that this factor may interfere with task performance, especially in the group of "bad readers".

Our paper presents strengths that should be discussed. The participants were selected very thoroughly from among students in their high school senior year or in their first college year, and according to their orthographic performance. The orthographic knowledge tasks administered to form the groups were very exhaustive, which allowed us to form the HSS and LSS groups with great knowledge of the participants' orthographic competence at the time of inclusion in the study, thus providing us with great intra-group homogeneity regarding their current orthographic skills. Moreover, the HSS and LSS participants showed small differences in reading speed and comprehension; this fact guarantees that both groups have a normal reading ability. In addition, the fact that all of the participants, both the HSS and the LSS, were students from the same school grade makes it unlikely that there were great differences between the general intellectual functioning of both groups. All this means that we can be reasonably sure that our groups only present differences in their long term orthographic skills. It is important to note that our study, jointly with the study of Richards et al. (2006), are the only ones that study the pseudohomophone errors processing in groups of persons selected by their previous level of orthographic knowledge (HSS and LSS groups).

Another strength is the fact that this is one of the few papers to explore the patterns of activation of brain areas during the recognition of pseudohomophone orthographic errors by comparing non-dyslexic participants with a high and a low orthographic knowledge, and one of the few performed in a shallow orthography. As mentioned above, this type of error is characteristic of transparent or consistent orthographies, and especially of the Spanish spoken in different parts of Latin America and Europe. In this sense, our results are particularly interesting, given that this type of orthographic error is characteristic and exclusive of transparent languages, where reading as a cognitive function has its own distinctive features.

Yet another strength is the fact that our work provides some evidence of brain automated orthographic processing in anterior brain regions. This phenomenon has been observed in tasks with orthographic components that activate temporal-occipital areas (Cone et al., 2008). The letter-searching task in our work is a good paradigm to elicit the automated orthographic processing. Additionally, this is one of the few works to relate the right frontal inferior activity to the long term orthographic processing.

To sum up, our work suggests that the HSS group was able to successfully perform the orthographic error decision task and showed activations in the right inferior frontal regions that have been mentioned in some studies with the long orthographic processing. On the other hand, the LSS group was not able to perform the same task successfully and showed a pattern of brain activations that included temporal, frontal and subcortical regions. Further studies should be conducted to determine whether the patterns of activation observed in this study appear in spotting tasks for other types of orthographic errors or if, instead, spotting pseudohomophone errors activates a pattern in good and bad spellers somewhat different from that of other types of errors.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

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PLEASE INSERT APPENDIX A HERE

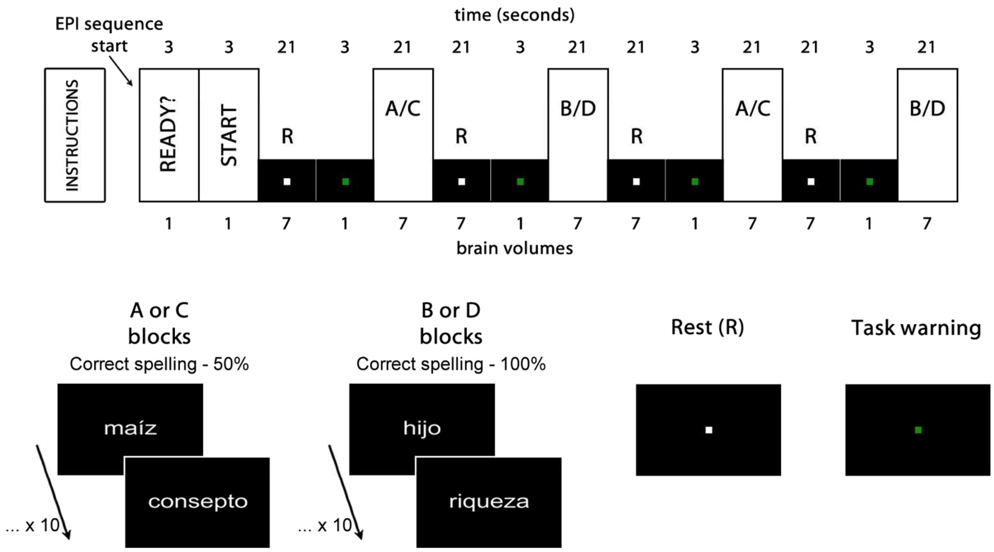

Figure 1. Experimental design. Rest (R) and activation blocks A and B for the spelling recognition task, and C and D for the letter-searching task. The first two brain volumes were eliminated from the analysis, as well as the four task warning volumes. 'Maíz' (corn), 'hijo' (son) and 'riqueza' (wealth) are examples of correctly spelled words. 'Consepto' (concept) is an example of an incorrectly spelled word (pseudohomophone), with an s instead of a c, thus generating a pseudohomophone error.

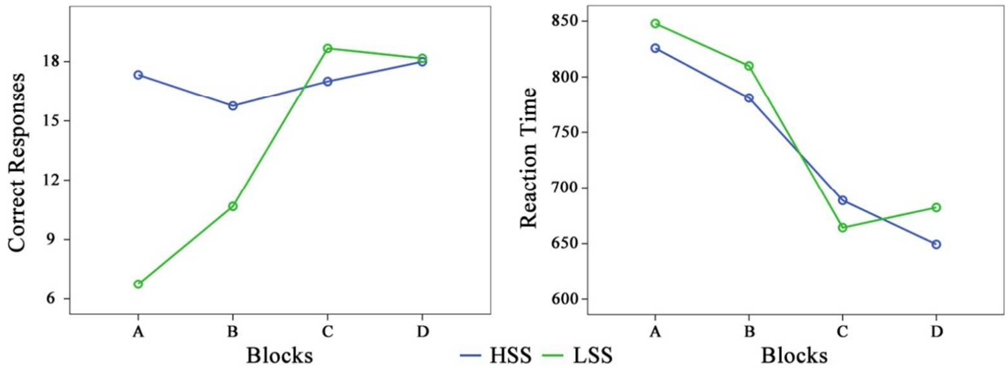

Figure 2. Effects on the number of correct answers and the reaction time according to the high (HSS) and low (LSS) spelling skills groups and their interaction with the type of task and block.

149x55mm (220 x 220 DPI)

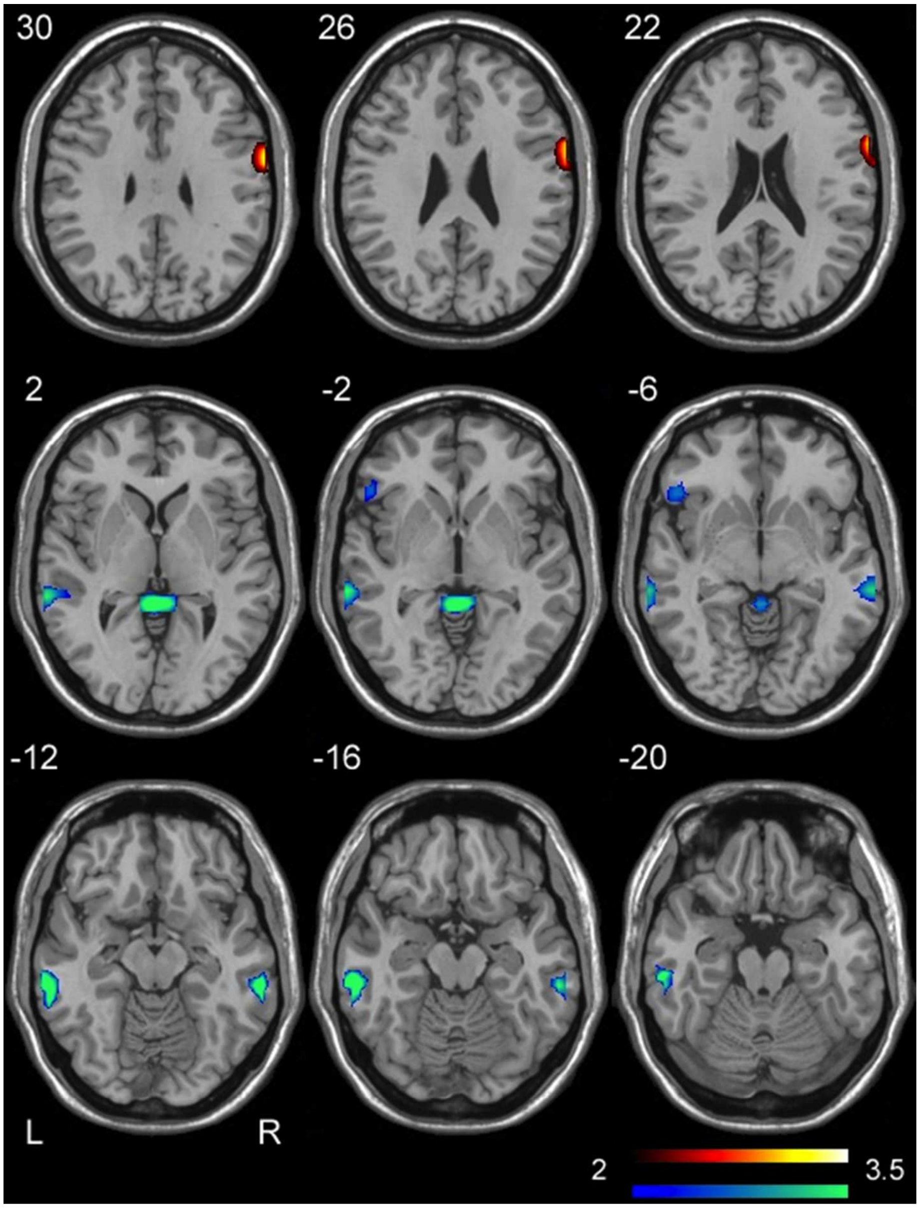

Figure 3. Statistical significance maps by regions for the spelling recognition task (A and B blocks) in the high (HSS, red-yellow) and low (LSS, blue-green) spelling skills groups.

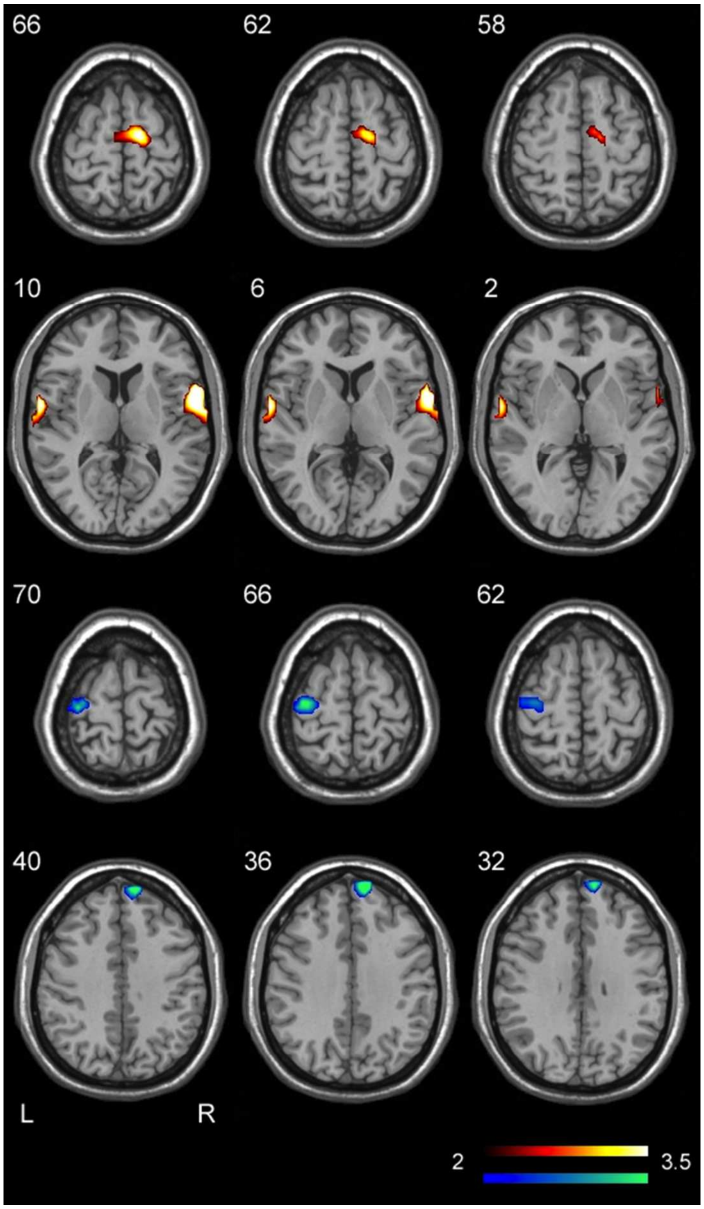

Figure 4. Statistical significance maps by regions for the letter-searching task (C and D blocks) in the high (HSS, red-yellow) and low (LSS, blue-green) spelling skills groups.

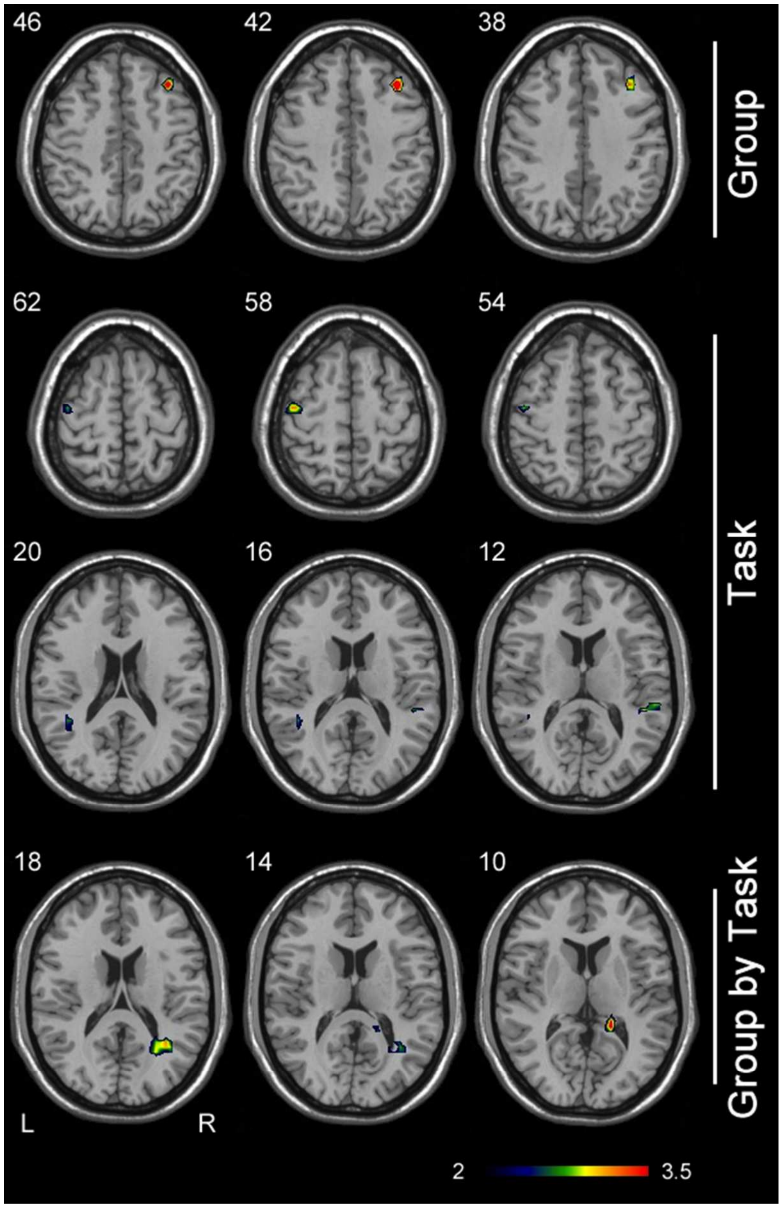

Figure 5. Statistical significance maps by regions based on the ANOVA analysis groups by tasks (blue to red show the statistical intensity effects).