Early Cerebral Constraints on Reading Skills in School-Age Children: An MRI Study

G. Borst[1,2,3,†], A. Cachia[1,2,3,4,†], C. Tissier[1,2,3], E. Ahr[1,2,3], G. Simon[1,2,3], and O. Houdé[1,2,3,4]

ABSTRACT— Reading relies on a left-lateralized network of brain areas that include the pre-lexical processing regions of the ventral stream. Specifically, a region in the left lateral occipitotemporal sulcus (OTS) is consistently more activated for visual presentations of words than for other categories of stimuli. This region undergoes dramatic changes at the functional and structural levels when children learn to read, but little is known about the effects of early cerebral constraints on reading skills. Using anatomical magnetic resonance imaging, we investigated whether the sulcal pattern of the lateral OTS—a stable brain feature—was associated with oral reading skills. The sulcal pattern of the left but not the right lateral OTS was associated with the number of words correctly read in 3 min. This study is the first to evidence that reading is affected by early cerebral constraints, such as the sulcal morphology of the left lateral OTS.

Reading is one of the core abilities that children need to master to be successful in school. From the perspective of mind, brain, and education, investigating the potential relations between the brain and school learning could be critical to understanding the factors that contribute to the acquisition of reading and individual differences in reading skills. In expert adult readers, reading relies on a left-lateralized network of brain areas that include the inferior frontal/precentral gyri, which is involved in verbal working memory and speech-gestural articulatory recoding for print; the dorsal temporoparietal circuit, which is associated with phonology-based reading processes; and the ventral occipitotemporal pathway which is related to visual orthographic features and lexical semantic processing in word recognition (Martin, Schurz, Kronbichler, & Richlan, 2015; Price, 2012). Ten-year-old children recruit the same brain areas as adults when they read (Gaillard, Balsamo, Ibrahim, Sachs, & Xu, 2003) but there are some differences in the degree of activation in certain regions, including the Supplementary Motor Area (SMA), which is engaged in word selection and encoding (Houdé, Rossi, Lubin, & Joliot, 2010). Reading also requires activating the ventral part of the visual stream for the pre-lexical stage of processing—that is, visual/orthographic processing. In the ventral visual stream there is a hierarchical posterior-to-anterior gradient for processing with posterior regions, such as the primary visual cortex, coding for simple visual features (e.g., segment orientation) and anterior regions, such as the left lateral occipitotemporal sulcus (OTS)—that is, sulci are parts of the cortex that are buried in the folds of the brain—coding for more complex and abstract visual forms of letters and words (Dehaene & Cohen, 2011; Vinckier et al., 2007). This left-lateralized region that is located in the lateral OTS is consistently more activated for visually presented words than other categories of stimuli (Dehaene & Cohen, 2011; Szwed et al., 2011) and becomes increasingly more responsive to visual presentations of letters and words with reading experience (Dehaene et al., 2010). Lesions in this area of the brain produce pure alexia, which is a pathology that is defined by a deficit in mapping visual inputs to visual word forms (Damasio & Damasio, 1983; Dejerine, 1892). Based on these findings, this region has been tentatively termed the "visual word form area" (VWFA; Cohen et al., 2000 but see Price & Devlin, 2011 for an alternative functional characterization of this region).

Although acquiring reading requires intense and prolonged learning, few studies have investigated functional (i.e., the network of brain activity) and structural (i.e., the

[1]LaPsyDÉ, CNRS Unit 8240
[2]University Paris Descartes, Institut de Psychologie
[3]University of Caen Basse-Normandie
[4]Institut Universitaire de France

Address correspondence to Grégoire Borst, University Paris Descartes, LaPsyDÉ, CNRS Unit 8240, 46 rue Saint-Jacques, 75005 Paris, France; gregoire.borst@parisdescartes.fr

[†] The authors contributed equally to this work.

volume, surface, and cortical thickness of the different brain areas) changes in the normal developing child's brain in response to acquiring this new skill (Schlaggar & McCandliss, 2007). A longitudinal study in 6-year-old children revealed that the selective activation of the VWFA for the presentation of words as measured by the electrophysiological activity (via EEG: electroencephalogram) and the level of deoxygenated blood (via fMRI: functional magnetic resonance imaging) of this region is related to the progressive acquisition of grapheme-phoneme correspondences while acquiring literacy (Brem et al., 2010). At a structural level (using an anatomical MRI), a study with children aged 9–10 years in which the volume of the gray matter (composed mostly of the body of the neurons) was measured via a voxel-based morphometry method (VBM) revealed that reading abilities were related to the gray-matter volume in the VWFA, the anterior part of the left inferior occipital gyrus, and the left thalamus (Simon et al., 2013). Moreover, a study with children aged 7–12 years in which the white-matter connections among brain areas was examined via diffusion tensor imaging (DTI) demonstrated that the microstructure of the white-matter fibers that connect the VWFA and the anterior and medial temporal lobe change—as indicated by an increase in the fractional anisotropy of the inferior longitudinal fasciculus—with reading proficiency and age (Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012).The results of the last two studies converge to show that the gray-matter volume of the VWFA that is located in the left lateral OTS and the white-matter microstructure of the fibers that connect this area to the anterior and medial temporal lobe—that is, two quantitative structural characteristics of the brain—are affected by age (i.e., brain maturation) and acquiring reading (i.e., prolonged learning).

In addition, a longitudinal MRI study (Myers et al., 2014) revealed that an increase in white-matter volume in the left temporoparietal region between kindergarten and Grade 3 predicts reading ability at Grade 3 above and beyond other measures (i.e., family history, socioeconomic status, and pre-reading cognitive abilities). Finally, a longitudinal fMRI study demonstrated that presenting letters elicits bilateral activation in the temporoparietal regions in 5-year-old children who have on-track pre-literacy skills and those who are at-risk of developing reading disorders. Three months later, presenting letters elicited a bilateral activation in the temporoparietal regions in 5-year-old children who had on-track pre-literacy skills, while children who were at-risk of developing reading disorders, presenting letters produced bilateral activation in this region and additional activation in the prefrontal areas to compensate for their reading difficulties (Yamada et al., 2011).

Finally, using a quantitative method to analyze the depth map on the white-matter surface (Im et al., 2010)—that is, the depth of the brain sulci—Im, Raschle, Smith, Ellen Grant, and Gaab (2015) reported that there was an abnormal sulcal pattern in a large region that covered several sulcal folds in both the parietotemporal and occipitotemporal regions in school-age children (84–155 months) who had developmental dyslexia (DD) and preschool/kindergarteners who had a familial risk for DD (59–84 months).

However, the brain's structural characteristics do not provide information on possible early cerebral constraints on reading abilities because they are affected by brain maturation (Giedd & Rapoport, 2010) and learning (Zatorre, Fields, & Johansen-Berg, 2012). Thus, to evaluate early cerebral constraints on reading abilities it is important to examine structural characteristics of the brain that are not affected by these two factors. The morphology of the sulci (i.e., a *qualitative* characteristic) is a good candidate for investigating early cerebral constraints on cognitive abilities because it is determined in utero (Mangin, Jouvent, & Cachia, 2010) and remains stable with age (Sun et al., 2012). Sulcal patterns result from in utero processes that shape the cortex anatomy from an initially smooth structure to a highly convoluted surface (Mangin et al., 2010; Welker, 1988). Several factors contribute to the neurodevelopmental processes during in utero life that shape the folded cerebral cortex, including differential tangential expansion (Ronan et al., 2014) and structural connectivity through axonal tension forces (Dehay, Giroud, Berland, Killackey, & Kennedy, 1996; Hilgetag & Barbas, 2006; Van Essen, 1997). The connectivity constraints lead to a compact layout that optimizes the transmission of neuronal signals between brain regions (Klyachko & Stevens, 2003) and brain network functioning. Many genetic programs, neurochemical processes, and environmental factors contribute to the early developmental process from neuronal migration to cortex sulcation (Barkovich, Guerrini, Kuzniecky, Jackson, & Dobyns, 2012; Rakic, 2004, 2006; Welker, 1988). Variations in some of these factors can presumably have an effect on the OTS sulcal pattern.

In addition, unlike quantitative features of the cortical sheet, such as thickness, surface area (Giedd & Rapoport, 2010), and curvature/gyrification (Armstrong, Schleicher, Omran, Curtis, & Zilles, 1995; Li et al., 2014; Raznahan et al., 2011; White, Su, Schmidt, Kao, & Sapiro, 2010)—which can take decades to attain the levels observed in adulthood—the qualitative pattern formed by the characteristic set of primary, secondary, and tertiary folds, or sulci, seen in human adulthood is already evident at birth (Chi, Dooling, & Gilles, 1977; Mangin et al., 2010; Zilles, Palomero-Gallagher, & Amunts, 2013). Inter-individual variation in this qualitative sulcal pattern has therefore been used as a marker for prenatal differences.

Using this approach, research has demonstrated that the sulcal pattern on the anterior cingulate cortex (ACC) contributes to cognitive inhibitory control efficiency—that is, the ability to inhibit a prepotent response (Diamond, 2013)—in 9-year-old children (Cachia et al., 2014) and adults (e.g., Fornito et al., 2004; Huster et al., 2009). Moreover, a longitudinal study revealed that the sulcal morphology on the ACC for children at age 5 explained inhibitory control efficiency at age 5 as well as 4 years later (Borst et al., 2014).

The present study investigated the potential effect of the sulcal morphology of the lateral OTS on reading skills of typically developing children. This is an important question because the sulcal morphology of the brain offers a window on the potential early (i.e., fetal) constraints of the brain on the acquisition of reading later in life. In other words, this study might inform us as to whether individual difference in oral reading skills of typically-developing children is associated mainly with environmental factors at the time children learn to read (such as the pedagogy used to teach reading) but also on a pre-existing condition related to the structure of the brain defined in utero. As such, we asked 9- and 10-year-old children to complete the Alouette-R test (Lefavrais, 2005), which is a standardized test for oral reading in French, and we identified the qualitative sulcal pattern on the lateral OTS with a three-dimensional, mesh-based reconstruction of the cortical folds that was based on the anatomical (T1) images for each child's brain (e.g., Borst et al., 2014; Cachia et al., 2014). Using the classification proposed by Ono, Kubik, and Abernathey (1990), we determined whether the lateral OTS was continuous or interrupted in the left and right hemispheres of each child's brain (see Figure 1). This anatomical criteria was a good candidate for testing early cerebral constraints in this region. Given (a) that difference in the sulcal morphology of a brain area is associated with white-matter connectivity (Van Essen, 1997) and microstructure difference of that cortical area (Fischl et al., 2008) and (b) that difference in the white-matter connectivity (e.g., Yeatman et al., 2012) and the microstructure (e.g., Simon et al., 2013) of the VWFA is associated with difference in reading skills in typically developing children, we expected difference in the sulcal morphology of the VWFA to be associated with difference in oral reading skills. Because pre-lexical processing in reading elicits stronger activation in the left lateral OTS (Dehaene & Cohen, 2011), we believed that the sulcal pattern of the left lateral OTS, but not the right, should be associated with performance on the Alouette-R test.

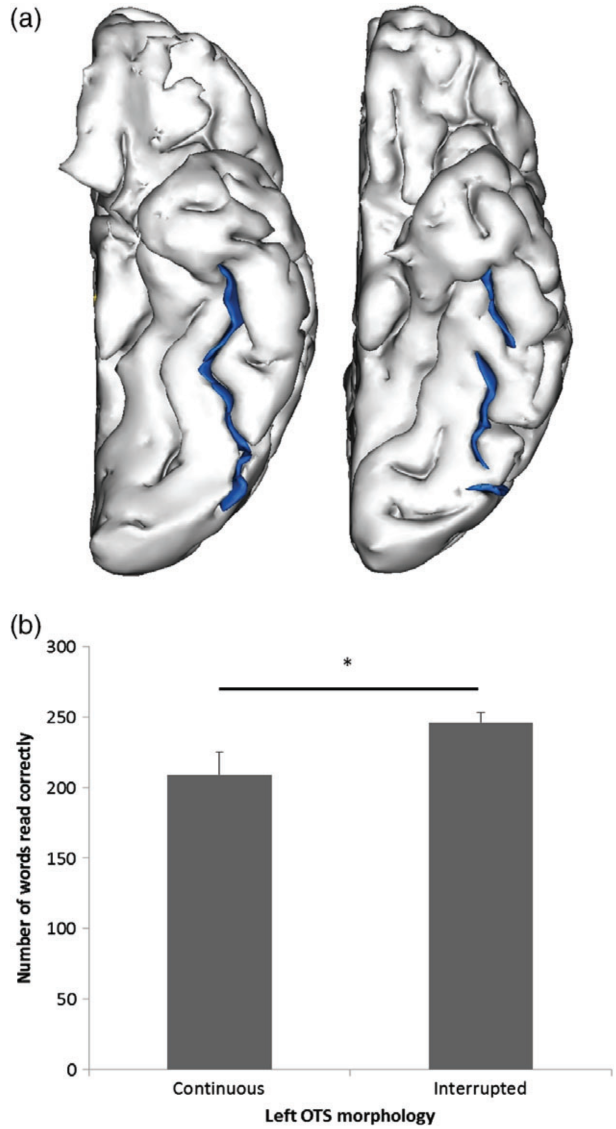

Fig. 1. The lateral OTS sulcal pattern classification (a) and its effect on the number of words read correctly (b). (a) Examples of an interrupted (on the left) and a continuous (on the right) left lateral OTS (sulci are depicted in blue on the cortical surface). (b) The number of words read correctly on average by children with continuous or interrupted left OTS. Error bars depict standard error of the mean, $^{*}p < .05$.

METHOD

Participants

Sixteen right-handed typically developing children (mean age = 9.97 ± 0.67 years; 8 females) were recruited from a public school in Caen (France). They presented with no history of neurological impairment or learning disability, including reading impairments. Parents completed a detailed biographical questionnaire to identify the prevalence of reading and language disorders in the family. All children were normally developing children who did not have reading disorders or histories of reading and language disorders in their families. Children and their parents provided written informed consent to participate in this study, which was approved by the ethical committee (CPP Nord-Ouest III, France).

Reading Test

We evaluated the children's reading proficiency with the Alouette-R test, which is a standardized test for assessing oral reading in French. This test requires oral reading of text that is composed of high-frequency or rare words and words that have low probability occurring in the context of the sentence in which they appear. The test is time-limited (3 min maximum to read the text). In the present study, we focused on reading accuracy, which was reflected by the number of words that were correctly read in 3 min. Children were tested after completing the MRI.

MRI Preparation and Acquisition

We acquired three-dimensional (3D) T1-weighted spoiled gradient images (field of view [FOV] = 256 mm, slice thickness = 1.33 mm, 128 slices, matrix size = 192×192 voxels, repetition time = 3,000 ms [TR], echo time = 35 ms [TE] and duration = 5 min 7 s) using a 3 T MRI scanner (Achieva, Philips Medical System, Netherlands). To prepare children for the MRI session, each child individually participated in a half-hour-long familiarization session at school the day prior to the MRI. The familiarization session consisted of a "statue game" that asked the child to stay as still as a statue in a toy tunnel that imitated the MRI scanner. The mock MRI scanner environment included recorded noises from the MRI sequences and a cardboard head coil. The day of the MRI session the same familiarization session was repeated before the actual MRI session. Then, after a short 5-min break, the T1 MRI was performed while the children passively watched a mute cartoon on an MRI-compatible screen to reduce motion, provide a positive experience, and decrease wait times (Lemaire, Moran, & Swan, 2009). Note that the head of the child was secured in a head coil with foam to further prevent any motion. The MRI session lasted approximatively 10 min with no break.

MRI Analysis

Image analysis was performed with the Morphologist toolbox using BrainVISA 4.2 software with standard parameters (http://brainvisa.info/). We used an automated pre-processing step to skull-strip the T1 MRIs and segment the brain tissues. We did not spatially normalize the MRIs to avoid potential biases resulting from shape deformations of the sulcus that may occur during the warping process. It is important to note that the pre-processing stage of the automated brain segmentation included a correction for the inhomogeneities that were induced by the acquisition process. This correction is achieved via estimating a smooth multiplicative field that minimizes the entropy of the intensity distribution (Mangin et al., 2004) and seeks to restore a meaningful relation between image intensity and tissue classes. The automatic segmentation of the cortical folds throughout the cortex was based on the skeleton of the gray-matter/cerebrospinal fluid mask (Mangin et al., 2004). This procedure allows one to obtain a stable and robust sulcal surface definition that is not affected by variations in cortical thickness or the gray/white-matter contrast. Images at each processing step for each MRI were visually checked and no motion artifacts or segmentation errors were observed.

OTS Classification

We visually inspected a three-dimensional, mesh-based reconstruction of the cortical folds using the BrainVISA software (http://brainvisa.info/; see Borst et al., 2014; Cachia et al., 2014) to classify the sulcal pattern on the lateral OTS. Our classification of the morphology of the lateral OTS was based on Ono et al.'s (1990) proposal. The sulcal pattern on the lateral OTS was characterized as *interrupted* when the lateral OTS had interruptions or gaps that were larger than 20 mm (a criteria similar to the one used for the sulcal morphology of the ACC; see, e.g., Fornito et al., 2004) and as *continuous* when there was no interruption or gap larger than 20 mm. The 20 mm interruption distance is arbitrary and is based on a criterion that was derived from previous sulcal studies in the ACC region (see, e.g., Fornito et al., 2004). This criterion is used to avoid identifying interrupted sulci when the interruption that is observed is likely an artifact that is due to a local segmentation error of the T1 MRI. The sulcal patterns of the lateral OTS were independently classified by three of the co-authors (Grégoire Borst, Arnaud Cachia, & Cloélia Tissier) using a dichotomous variable code for the presence of an interrupted versus continuous lateral OTS. Reliability was 100% (kappa = 1) among the three raters for the left and the right hemispheres.

RESULTS

On the reading test, children correctly read an average of 229.81 ± 36.7 words in 3 min, with a range of 111 words. The number of words correctly read by each child was within 1 standard deviation of the average number of words that were correctly read for their age class, which suggests that none of the children had reading disorders. Thus, we used the raw reading scores in the subsequent analyses. Finally, we found no significant correlation between age and the number of words correctly read, $r(14) = .28$, $p = .28$.

An analysis of the three-dimensional mesh-based reconstruction of the cortical folds revealed that continuous lateral OTS were found in 6 children in the left hemisphere and 12 children in the right hemisphere. This distribution of continuous and interrupted lateral OTS is consistent with the one reported by Ono et al. (1990).

To determine whether the sulcal pattern of the lateral OTS was associated with oral reading accuracy as measured by the number of words correctly read on the Alouette-R test, we performed multiple linear regressions with the number of words correctly read as the outcome variable and (a) the sulcal pattern of the lateral OTS in the left hemisphere, (b) the sulcal pattern of the lateral OTS in the right hemisphere, and (c) age in months as predictor variables.

The multiple linear regressions revealed that the three predictors accounted for 37.9% of the variance in the number of words correctly read, $F(3, 15) = 4.05$, $p < .05$, adjusted $R^2 = .379$. Importantly, the number of words correctly read was associated with the sulcal morphology of the left lateral OTS ($\beta = .62$, $p < .025$) but not the right lateral OTS ($\beta = .17$, $p = .47$) or with age ($\beta = .25$, $p = .31$). Importantly, children who had an interrupted lateral OTS ($M = 246.11 \pm 20.8$) read more words correctly than children who had a continuous lateral OTS ($M = 208.86 \pm 43.4$), $t(14) = 2.28$, $p < .05$, $d = 1.19$. Finally, 8% of the variance in the number of words correctly read was explained when age was the only predictor in the model, $F(1, 14) = 1.21$, $p = .28$, $R^2 = .08$, and 66% of the variance was explained when the morphology of the left lateral OTS was added to the model, $F(2, 13) = 4.88$, $p < .05$, $R^2 = .66$. The R^2-change (35%) was significant, $F(1, 13) = 7.88$, $p < .025$.

We found the same pattern of results when we only included the sulcal morphology of the left and right OTS in the multiple linear regression analysis. The two predictors accounted for 33.5% of the variance in the number of words correctly read, $F(2, 15) = 4.78$, $p < .05$, adjusted $R^2 = .325$. Importantly, the number of words correctly read was associated with the sulcal morphology on the left lateral OTS ($\beta = .55$, $p < .025$) but not the sulcal morphology on the right lateral OTS ($\beta = .39$, $p = .09$).

DISCUSSION

As expected, we found that, after controlling for the effect of age, the sulcal pattern of the left but not the right OTS predicted oral reading accuracy as measured by the number of French words correctly read in 3 min. Specifically, children who had an interrupted left OTS had better reading accuracy than children who had a continuous left OTS. The selective effect of the sulcal pattern of the left OTS is consistent with fMRI studies that reported a VWFA activation in the left OTS in response to the presentation of written words (Dehaene & Cohen, 2011). Thus, we provide the first evidence to date that a stable characteristic of the brain determined in utero (Mangin et al., 2010) that is not affected by brain maturation and prolonged learning (Sun et al., 2012), including learning to read in an area of the brain that is consistently activated in reading, namely the left OTS, is associated with oral reading accuracy.

We suspect that the relation between the sulcal morphology of the left OTS and oral reading accuracy might be a consequence of the association between sulcal morphology and white-matter connectivity (Hilgetag & Barbas, 2006; Van Essen, 1997). Specifically, the morphology of the left OTS could be associated with oral reading accuracy by affecting the connectivity between the VWFA and the anterior and medial temporal lobe. This interpretation is consistent with a previous study that showed that the connectivity between these two regions in 7–12-year-old children increases with reading efficiency and age (Yeatman et al., 2012). In addition, the effect of the sulcal pattern of the left OTS on reading skills might be mediated by the effect of the sulcal pattern of the left OTS on the activation and/or structural characteristics (e.g., gray-matter thickness or volume) of the VWFA. Indeed, previous studies have demonstrated (a) that the sulcal morphology of a brain area could affect the activation and the structure of this area (Amiez et al., 2013; Fornito et al., 2008; Paus, Koski, Caramanos, & Westbury, 1998) and (b) that the activation and the structure of the VWFA is associated with reading skills (Brem et al., 2010; Simon et al., 2013). Moreover, an interrupted left OTS might confer an advantage for reading accuracy because the sulcal morphology of a given brain area affects white-matter connectivity (Dehay et al., 1996; Van Essen, 1997) and the microstructure (Fischl et al., 2008) of that cortical area. Given that a DTI study with children aged 7–12 years demonstrated that the microstructure of the white-matter fibers that connect the VWFA and the anterior and medial temporal lobe change with reading proficiency and age (Yeatman et al., 2012) and that the sulcal morphology of a region affects its white-matter connectivity (Dehay et al., 1996), we speculate that an interrupted left OTS might be associated with better reading skills because of a local change of white-matter connectivity and integrity of the VWFA. Note however that this is purely speculative at this point and that more studies are needed to provide a causal explanation as to why an interrupted OTS provides an advantage for reading skills. Finally, given that the visual presentation of words and letters consistently activates the so-called VWFA, we suspect that that interruptions in the left lateral OTS that are located on or near the VWFA (Talairach coordinates $x = -43$, $y = -54$, $z = -12$, see Cohen et al., 2002) would be more strongly associated with reading skills than interruptions on other parts of this sulcus.

Recent research also demonstrates that the volume of the left OT area (Raschle, Chang, & Gaab, 2011) and the organization of the connection between the VWFA and anterior regions of the brain, such as pars triangularis (Saygin et al., 2013; Vandermosten et al., 2015)—that is, a white-matter track that is involved in orthographic processing—differ between pre-reading children at risk or not at risk for developing dyslexia. In addition, a recent study showed an abnormal sulcal pattern in the parietotemporal/occipitotemporal area in school-age children who had DD and in preschool/kindergarteners who had a familial risk for DD (Im et al., 2015). These findings converge to show that the morphology of the brain in pre-reading children predicts reading skill acquisition later in life. Our finding is in line with this research and suggests an intriguing hypothesis, which posits that some of these early differences in the morphology of the areas involved in the reading network might be related to the sulcal morphology of the VWFA as determined in utero. Finally, because the present study was restricted to typically-developing children, any inference regarding the potential effect of the sulcal morphology of the OTS on the development of reading deficits should be taken with caution. That said, we note that Im et al. (2015) provided convergent evidence that the sulcal pattern of the OTS affected reading skills in children with DD and in preschool/kindergarteners who had a familial risk for DD. Thus, our study provides evidence that the sulcal morphology of the OTS contributes to difference in reading skills not only of children with reading deficits but also of typically developing children.

We note that the effect of the morphology of the left lateral OTS on reading could be mediated by other variables, such as its effect on orthographic processing, which, in turn, would affect reading ability. However, a lesion on the area located in the lateral OTS produces pure alexia, which is defined by deficits in mapping visual inputs to visual word forms without orthographic deficits—that is, patients suffering from pure alexia have no writing deficits (Damasio & Damasio, 1983; Dejerine, 1892).

The present finding has important implication for education. Acquiring reading skills is generally considered a seminal example of how education can induce changes in children's brains at functional and structural levels (Dehaene & Cohen, 2011). Thus, individual differences in reading are generally attributed to quantitative characteristics of the brain that are, by definition, affected by brain maturation and intense training—including when children learn to read. Our results suggest that some individual differences in reading skills could be partially attributed to characteristics of the brain that are determined in utero long before children start to learn to read. The sulcal morphology of the brain may constitute an early predisposition for developing poor reading skills. Thus, the question for teachers is not only what are the best pedagogical strategies to teach reading but also how to identify children who might be at risk for developing poor reading skills. We do not argue that all children should be scanned to determine the sulcal morphology of their brains. Rather, we suggest that more attention should be given to early factors that might contribute to difficulties in learning to read. Our finding complements other research that has shown that individual differences in reading could partially be predicted by the brain's functional and structural characteristics in pre-reading children (e.g., Bach, Richardson, Brandeis, Martin, & Brem, 2013). To provide a better comprehension of the way the sulcal pattern of the OTS affects reading skills, future researches should extend our finding to other visual processing that elicit activation of the OTS (such as face processing), to children with reading deficits, and to a sample of readers tested with a standardized measure of reading.

In conclusion, we provided the first study to show that the sulcal morphology of the left OTS—a qualitative feature of the brain that is determined in utero and is not affected by learning (such as learning to read)—partially explains oral reading skills in 10-year-old children. This result may be important for the early detection of neurodevelopment disorders such as DD because this dyslexia alters the VWFA's activation (e.g., Hoeft et al., 2007), gray- and white-matter volume (Raschle et al., 2011; Saygin et al., 2013) and connectivity (e.g., Vandermosten et al., 2015)—three characteristics of the VWFA that can be potentially affected by the sulcal morphology of the left OTS. A clear limitation of the present study is the small sample size, which is a consequence of the difficulty of conducting brain imaging studies with young children. Additional research with larger samples is needed to demonstrate the robustness of the effect of the sulcal pattern of the left OTS on reading skills. Larger sample sizes would also be useful for determining whether the association between reading skills and the sulcal pattern of the left OTS is mediated by the effect of the sulcal pattern of the left OTS on the functional and structural characteristics of the VWFA and the connectivity of this area with other regions in the reading network.

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