



# Bilingualism yields language-specific plasticity in left hemisphere's circuitry for learning to read in young children



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## ABSTRACT

How does bilingual exposure impact children's neural circuitry for learning to read? Theories of bilingualism suggests that exposure to two languages may yield a functional and neuroanatomical adaptation to support the learning of two languages (Klein et al., 2014). To test the hypothesis that this neural adaptation may vary as a function of structural and orthographic characteristics of bilinguals' two languages, we compared Spanish-English and French-English bilingual children, and English monolingual children, using functional Near Infrared Spectroscopy neuroimaging (fNIRS, ages 6–10, N =26). Spanish offers consistent sound-to-print correspondences (“phonologically transparent” or “shallow”); such correspondences are more opaque in French and even more opaque in English (which has both transparent and “phonologically opaque” or “deep” correspondences). Consistent with our hypothesis, both French- and Spanish-English bilinguals showed hyperactivation in left posterior temporal regions associated with direct sound-to-print phonological analyses and hypoactivation in left frontal regions associated with assembled phonology analyses. Spanish, but not French, bilinguals showed a similar effect when reading Irregular words. The findings inform theories of bilingual and cross-linguistic literacy acquisition by suggesting that structural characteristics of bilinguals' two languages and their orthographies have a significant impact on children's neuro-cognitive architecture for learning to read.

## 1. Introduction

How does a bilingual child learn to read in two different languages? Children who receive early and systematic exposure to two languages achieve high proficiency in each language (Jasińska and Petitto, 2013, 2014; Kovelman et al., 2008a; Neville, 1993; Petitto et al., 2012; Weber-Fox and Neville, 1996). Neuroimaging evidence suggests that such early and systematic bilingual exposure may result in a “neural signature” of bilingualism, or experience-driven changes in neural activation supporting learning two languages (Jasińska and Petitto, 2013, 2014; Kovelman et al., 2008b, 2008c); that is, bilingual acquisition should yield quintessentially “bilingual” rather than “monolingual” outcomes (Grosjean, 1989). A bilingual child's two languages are well known to interact with each other during acquisition (Kroll et al., 2008), and structural characteristics of the two languages and orthographies could impact how a bilingual child learns to read and a child's

brain organization for reading. To test this hypothesis, we compared French-English and Spanish-English bilingual children to English monolingual children to examine how bilingual exposure across different languages (Spanish and French) impacts children's English reading performance and underlying neural activation patterns.

Literacy acquisition research has now extensively mapped both the linguistic and cognitive skills, and their corresponding neural networks, that underlie learning to read in young monolingual readers of English and many other languages (McNorgan et al., 2011; Perfetti et al., 2006, 2007; Pugh et al., 2001; Sandak et al., 2004). Three key findings have emerged. First, learning to map language sounds (phonology) onto orthographic representations (e.g., letters) is foundational for learning to read across all orthographies (Ho and Bryant, 1997; Ziegler and Goswami, 2005). Second, improvement in this ability is supported by changes in the functionality and interconnections between left inferior frontal, temporo-parietal and occipito-temporal

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regions for language analyses and mapping linguistic representations onto print (Hoefl et al., 2007; Pugh et al., 2001). Third, orthographic experiences can leave a language-specific impact on individuals' brain organization for reading (Perfetti et al., 2013).

For proficient readers, word knowledge is comprised of tightly interconnected units of sound, meaning and orthography (Perfetti and Hart, 2002; Perfetti et al., 2006, 2007). Reading primarily consists of processes distributed over these levels of linguistic representation (phonology, semantics, orthography), according to contemporary computational models of reading, known collectively as “triangle models of reading” (Boukrina and Graves, 2013; Harm and Seidenberg, 2004; Hoffman et al., 2015; Rueckl, 2016). To decode a word and access its meaning, orthographic representations activate corresponding phonological and semantic networks. Mapping phonemes to graphemes is an important step in learning to read (Lieberman et al., 1989). Skilled reading involves this connection among orthography-phonology-semantic (whereby access to semantic representations is mediated by phonological representation), as well as a direct orthography-semantic connection (whereby, semantic representations are directly retrieved based on orthographic structure). The division of labor among these pathways changes over development, however, all connections remain crucial to skilled word identification (Harm and Seidenberg, 1999, 2004). With increased reading experience and skill, readers may rely to an increasing degree on direct associations between orthography and semantics (Share, 1995), through print-meaning or orthography-semantic mapping, also referred to as the *lexical route* (Harm and Seidenberg, 2004; Plaut et al., 1996; Seidenberg and McClelland, 1989).

Languages vary in the regularity with which phonological units map onto print. Languages that have a direct one-to-one mapping between sound and print are *transparent orthographies*; these include, for example, Spanish and Finnish. On the other hand, languages that have irregular mapping between sound and print are *opaque orthographies*; these include, for example, English, and logographic languages such as Chinese. The word “dog” is an example of regular or transparent sound-to-print mapping and the word “neighbor” is an example of irregular or opaque sound-to-print mapping. These differences have consequences for learning to read (Ziegler and Goswami, 2005). According to the orthographic depth hypothesis, readers of transparent orthographies rely to a greater extent on the orthography-phonology-semantic pathway as compared with readers of opaque orthographies, who rely to a greater extent on the orthography-semantic pathway (Frost et al., 1987). For example, a comparison of reading development across five languages (from transparent to opaque: Finnish, Hungarian, Dutch, Portuguese, and French) found differences in reading performance modulated by orthographic transparency (Ziegler et al., 2010). Phonological awareness was a robust universal predictor of reading outcomes in the sample of 1,265 Grade 2 children (~8 years old), however, the contribution of phonology to reading was more robust for transparent versus opaque orthographies (Ziegler et al., 2010). Therefore, for a young beginning reader of Finnish, phonological awareness has a more robust role in reading than for a young beginning reader of French.

Orthographic differences also have consequences for the extent to which readers engage left frontal regions that support complex sound-to-print assembly versus posterior-temporal regions that help integrate orthographic, phonological, and lexico-semantic rules (Das et al., 2011; Jamal et al., 2012). The temporo-parietal system, including the angular and supramarginal gyrus, is involved in lexical-semantic processing and has an important role in converting orthography into phonology (Moore and Price, 1999). The left superior temporal gyrus (STG, BA 21/22/42) is important in phonological processing (e.g., Petitto et al., 2000; Zatorre and Belin, 2001). The anterior reading system includes the left inferior frontal gyrus (LIFG); the more posterior portion is involved in sublexical phonological coding, phonological memory, and syntactic processing (Pugh et al., 2001) and the more anterior portion

is involved in lexical access and semantic retrieval (Poldrack et al., 1999). This architecture for reading is part of a larger cortical network supporting language and other cognitive functions, and is adapted to the task of reading. For example, the LIFG is involved other aspects of language processing, such as articulatory motor planning (Davis et al., 2008).

For instance, a comparison between adult monolingual readers of English and Italian during a pseudoword reading task revealed that English readers showed stronger activation of left inferior frontal regions – associated with lexical access, while Italian readers showed stronger activations in left superior temporal regions – associated with phonological processing (Paulesu et al., 2000). How then might early-life exposure to both a phonologically-transparent and a phonologically-opaque language impact bilingual children's neural architecture for reading?

Newly-emerging research suggests that early bilingual exposure might change the manner in which young bilingual learners form the interconnections between phonology, meaning, and orthography. Importantly, the impact of bilingual exposure is thought to extend beyond individual literacy skills and impact the underlying architecture of children's emergent literacy (Proctor et al., 2006; Uchikoshi, 2012). Theories of bilingual language processing suggest that even when using only one of their languages, bilinguals have access to linguistic and orthographic representations of their other language (Kroll et al., 2008). Such tight interaction between bilinguals' two languages facilitates the sharing or “transfer” of literacy knowledge gained in one language towards learning to read in another language, bidirectionally (Proctor et al., 2010). For instance, several studies comparing Spanish-English or Italian-English bilinguals to English monolinguals revealed that bilingual learners relied more heavily on phonology to read words (Kremin et al., 2016) and/or outperformed English monolinguals on English phonological literacy tasks (D'Angiulli et al., 2001; Kovelman et al., 2008a), suggesting that literacy skills gained in a phonologically-transparent orthography (Italian, Spanish) can transfer towards learning to read in a more opaque orthography (English). On the other hand, Chinese-English bilinguals might weigh more heavily on meaning-to-print interconnections for learning to read in English, as compared to English monolinguals, whereas Spanish-English bilinguals might weigh more heavily on sound-to-print interconnections for learning to read (Hsu et al., 2016; Ip et al., 2016).

The lion's share of developmental bilingual literacy research has been conducted with bilingual adults who either learned two languages at the same time or sequentially during childhood (e.g., Abutalebi et al., 2013; Berken et al., 2015). The findings generally suggest that for sequential bilingual learners, there is an impact of first language exposure on their second language processing. For instance, studies by Tan et al. (2003) and Das et al. (2011) investigated bilinguals who learned to read in either Chinese or Hindi first, and English second (relative to English, Chinese is more phonologically-opaque and Hindi is more phonologically-transparent). As compared to English monolinguals, Chinese-English bilinguals showed greater activation in left frontal regions associated with mnemonic and analytical demands for complex sound-to-print mappings (Tan et al., 2003). By contrast, as compared to English monolinguals, Hindi-English bilinguals showed greater activation in left temporo-parietal regions associated with more direct sound-to-print mappings (Das et al., 2011).

Nevertheless, these data also raise the question of whether early and systematic bilingual experiences yield changes in neurodevelopmental patterns of activation for reading (Jasińska and Petitto, 2013; Kovelman et al., 2008a). Unfortunately, little is known about the brain bases of bilingual literacy during the early periods when children establish the basic literacy skills (Hernandez et al., 2015), especially in relation to bilingual speakers of different languages and monolinguals. Therefore, to shed light on the possible impact of dual language exposure on children's neural architecture for learning to read, we compared young Spanish-English and French-English bilinguals to

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