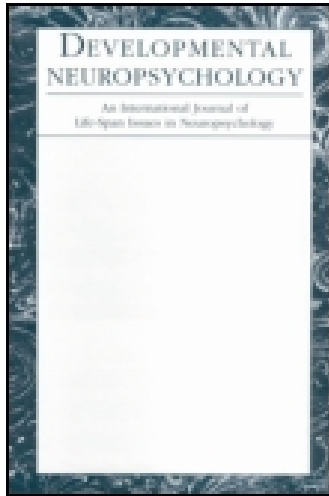


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Development of Neural Systems for Reading in the Monolingual and Bilingual Brain: New Insights From Functional Near Infrared Spectroscopy Neuroimaging

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Development of Neural Systems for Reading in the Monolingual and Bilingual Brain: New Insights From Functional Near Infrared Spectroscopy Neuroimaging

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What neural changes underlie reading development in monolingual and bilingual children? We examined neural activation patterns of younger (ages 6–8) and older (ages 8–10) children and adults to see whether early-life language experience influences the development of neural systems for reading. Using functional Near Infrared Spectroscopy, we observed an age-related shift in neural recruitment of language areas (left inferior frontal gyrus [LIFG], superior temporal gyrus [STG]). Bilinguals showed a greater extent and variability of neural activation in bilateral IFG and STG, and higher cognitive areas (dorsolateral prefrontal cortex, rostralateral prefrontal cortex). This bilingual “neural signature” reveals the extent that neural systems underlying reading development can be modified through differences in early-life language experience.

Reading is a complex process typically acquired through explicit training and involves all levels of language organization and processing, including, phonological, morphological, syntactic, and semantic (Catts, Fey, Zhang & Tomblin, 2001; Wagner et al., 1997). Skilled reading involves mapping visual (orthographic) word information onto phonological and semantic representations, the lion’s share of which is performed by a network of left-hemisphere frontal, temporoparietal, and occipitotemporal cortical regions (Turkeltaub, Gareau, Flowers, Zeffiro & Eden, 2003; Price, 2000). Little is known about the brain changes that underlie successful reading across early development in the monolingual child, and even less is known about the brain changes associated with reading in the healthy, typically developing bilingual child. Here we examine the neural activation patterns of younger beginning readers and older skilled readers to see what neurodevelopmental changes support typical reading acquisition and whether monolingual versus bilingual language experience can impact reading processing across early life.

Phonological awareness, or the ability to recognize and manipulate the sound units of language, is a crucial aspect of reading acquisition (Goswami, 2008; Turkeltaub, et al., 2003; Wagner et al., 1997). Indeed, poor phonological skills are the hallmark of poor readers (Wagner et al., 1997). The young child's ability to match phonemic (sound) segments of language onto their corresponding graphemes (letters), otherwise known as grapheme-to-phoneme correspondence, is a central capacity underlying successful reading development (Goswami, 2008; Wagner et al., 1997). Understanding the grapheme-to-phoneme correspondence is challenging for the younger reader because the relationship between a sound and the letter that it stands for is not always transparent. This is particularly the case in English, where many words have irregular spelling (termed "deep orthography"), that is, sounds and letters do not have a one-to-one mapping. For example, the word *circus*, the letter "c" corresponds to the phoneme /s/ at the beginning of the word, but corresponds to the phoneme /k/ in the middle of the word.

Different aspects of phonological processing are thought to be important for successful reading acquisition. Phonological working memory is one key component of skilled reading, as children have to remember the mappings between sound sequences and the corresponding letters. Thus cognitive factors, especially the maturation of working memory and attention, are key processes crucially involved in reading acquisition. However, a younger reader's phonological skills are a strong predictor of later reading achievement independent of general cognitive ability (Muter, Hulme, Snowling, & Taylor, 1997; Wagner et al., 1997).

Irrespective of typological differences across languages and their writing systems (e.g., alphabetic versus nonalphabetic), research has shown that all very young readers access language sounds in association with print (Goswami, 2008) and this appears to be true even in the very young Chinese reader (Wang, Yang, & Cheng, 2009). As children move from early to skilled readers, they move from using phonetic cues to decode words, and begin to consolidate commonly occurring letter sequences (such as -tion) into clusters, processing these clusters as units (Turkeltaub et al., 2003; Wagner et al., 1997). Thus, whereas a younger reader relies heavily on the phonetic components of words (i.e., phoneme-to-grapheme correspondence skills), a more skilled older reader will utilize word-level reading skills, processing the whole word (Turkeltaub et al., 2003; Wagner et al., 1997). Over-reliance of phoneme-to-grapheme correspondence strategies by an older reader has been used as a predictor of reading delay and/or increased risk of developing a reading disorder (Barca, Burani, Di Filippo, & Zoccolotti, 2006; Wagner et al., 1997).

In monolinguals, the brain areas that make possible typical reading development included neural systems associated with visual perception and language abilities. Reading requires the brain's visual object-processing systems in order to interpret orthography as well as language processing systems in order to link orthography with phonology and meaning. These neural regions include the left mid-fusiform gyrus, also referred to as the "visual word form area" (VWFA, Brodmann's area (BA) 37), the inferior parietal lobule (IPL), which includes the angular and supramarginal gyri (BA 39 and 40), and "classic" language areas such as the left inferior frontal gyrus (LIFG), which includes pars triangularis, pars opercularis (Broca's area, BA 44/45) and pars orbitalis (BA 47), and the superior temporal gyrus (STG, BA 21/22/42).

The VWFA has a role in visual word recognition (McCandliss, Cohen, & Dehaene, 2003; Price, 2000). The IPL has an important role in converting orthography into phonology (Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995). The LIFG typically participates in syntax, morphology, semantics and phonology, including the search and retrieval of information

about the meanings of words (Foundas, Eure, Luevano, & Weinberger, 1998; Kovelman, Baker & Petitto, 2008b; Price, 2000). The STG is known to be important in phonological processing (e.g., Zatorre & Belin, 2001; Petitto, Zatorre et al., 2000). Further, the dorsolateral prefrontal cortex (DLPFC, BA 9/46) is involved in the lion's share of controlling working memory and attentional resources (Balconi, 2013; Fuster, 2008), which are critical components of reading.

Neuroimaging research has revealed clear brain changes in young children over time (Cepeda, Kramer, & Gonzales de Sather, 2001; Jasińska & Petitto, 2013). However, relatively little is known about how these brain changes impact and/or contribute to reading and reading success. Frontal cortex maturation is particularly protracted as compared to other cortical regions (Cone, Burman, Bitan, Bolger, & Booth, 2008). The left temporoparietal areas (STG, IPL) mature earlier and are involved in language and reading through adulthood, whereas maturation of the LIFG occurs later in life (Cone et al., 2008; Petitto et al., 2012). In a single-word reading task and verb generation task, adults showed greater recruitment of left frontal cortex (BA 44/46) relative to 7–10-year-old children; however, children showed greater recruitment of left extrastriate region (BA 18) relative to adults (Brown et al., 2005).

While much is understood about the monolingual child's early phonological processing, questions remain about its neural foundations. For the bilingual child even less is known. Bilingual children have two phonological systems, and demonstrate increased phonological awareness skills relative to monolinguals (Bialystok, Majumder, & Martin, 2003; Eviatar & Ibrahim, 2000; Kovelman, Baker, Petitto, 2008a). Bilingual school-aged children outperform their monolingual peers on measures of phonological awareness (Bialystok et al., 2003; Eviatar & Ibrahim, 2000; Kovelman et al., 2008a; Kuo & Anderson, 2012). Children educated in bilingual English–Spanish schools from monolingual English-speaking homes outperform children educated in monolingual English schools on a complex phonological awareness task requiring children to break apart a word into individual phonemes (Kovelman et al., 2008a). This bilingual phonological processing advantage is apparent early in life as revealed by behavioral differences in language discrimination (Werker, 2012) and patterns of neural activation in the bilingual and monolingual infant brain (Petitto et al., 2012). Petitto et al. (2012) measured neural activation patterns of younger (4–6 month) and older (12–14 month) monolingual and bilingual infants while they listened to phonetic contrasts in their native language (English) versus phonetic contrasts in a non-native language (Hindi). Bilingual infants demonstrate greater and longer neural sensitivity to universal phonetic distinctions at a time in development when monolingual infants can no longer make such discriminations. Congruent with universal phonetic discrimination, younger monolinguals showed more STG recruitment Non-Native contrasts as compared with older monolinguals. Both younger monolinguals and bilinguals showed similar neural activity for Native and Non-Native contrasts. However, older bilinguals showed greater STG activation for Non-Native contrasts, when monolinguals no longer make such discriminations. Early bilingual exposure may provide a linguistic “Perceptual Wedge” that extends infants' sensitivity to universal phonetic contrasts (Petitto et al., 2012; Jasińska & Petitto, 2011). This bilingual advantage in phonological processing is of great theoretical relevance to bilingual reading development given the fundamental role of phonology in emergent literacy. Moreover, the observed difference in neural activation patterns in the young bilingual versus monolingual suggests that the neurodevelopmental trajectories of the bilingual and monolingual brains differ from a young age. Indeed, neural activation differences are observed throughout development in school-aged children (ages 7–10): bilingual children show greater neural activation in left hemisphere language

areas when compared with their monolingual peers (Jasińska & Petitto, 2013). These functional activation differences between monolingual and bilingual children are accompanied by structural differences, particularly in white matter (Mohades et al., 2012). Similarly, in adults, differences between monolinguals and bilinguals in functional neural activation patterns are well documented (Kovelman et al., 2008a; Kovelman, Shalinsky, Berens, & Petitto, 2008; Proverbio, Cok, & Zani, 2002).

Here we ask, how do young bilingual children learn to read when they face the daunting task of phonological processing across two languages instead of one? To answer this question, similarities and differences in brain activity underlying the development of reading in bilingual and monolingual children were compared using a single-word reading task that participants performed while undergoing functional near infrared spectroscopy (fNIRS) neuroimaging. fNIRS has significantly increased our ability to image human language and higher cognition. fNIRS provides good anatomical localization, excellent temporal resolution (fNIRS has a sampling rate of $10 \times$ per s10 Hz, while functional magnetic resonance imaging (fMRI) has a sampling rate of approximately $1 \times$ every 2–3 s), tolerates movement, is quiet and “child-friendly,” and thus exceptionally well suited for the study of language (see methods below for a more detailed description; see also Quaresima, Bisconti, & Ferrari, 2012, for a review).

Younger and older monolingual and bilingual children and adults read aloud regularly spelled, irregularly spelled, and nonsense words. Regular words have a one-to-one grapheme-to-phoneme correspondence, for example *stop*. Irregular words do not sound how they are spelled, for example, *debt*. Nonsense words are pronounceable, but nonexistent in the native language and also have a one-to-one grapheme-to-phoneme correspondence, for example *dask*. The use of these three categories of words permits powerful insight into the type of processing that the young child is using when reading. If relying predominantly on phonological processing through a grapheme-to-phoneme correspondence strategy, the child will correctly read a regularly spelled word and a nonsense word. Note that this phonological processing strategy would fail for irregularly spelled words. By contrast, if relying predominantly on the whole-word processing strategy, here the child will correctly read both regularly spelled and irregularly spelled words.

In the present study, we ask three fundamental questions: (1) What brain sites and systems correspond to a child’s early and later reading milestones over time? (2) What are the neurodevelopmental changes in these brain sites and systems across early and later reading milestones? This would reveal how neurodevelopmental changes contribute to successful reading acquisition across development. We specifically examine the brain tissue and systems that make possible early and later reading skills, including the neural systems underlying the processing of the sound patterns of words and those that participate in the processing of whole words (i.e., STG, LIFG, respectively). (3) Are neurodevelopmental changes similar or dissimilar in monolingual and bilingual children? Comparing patterns of neural activation in monolingual and bilingual readers will yield insights into whether language experience can modify the neurodevelopmental changes that support reading in ways that may be advantageous to the bilingual reader. We further test two hypotheses. Hyp 1: If monolingual and bilingual developing brains show *different* patterns of neural activation while reading, this would lend support to the bilingual “neural signature” hypothesis (Kovelman et al., 2008b; Jasińska & Petitto, 2013); that is, early dual language exposure can modify the language-dedicated neural sites that support the development of reading. Hyp 2: If monolingual and bilingual developing brains show *similar* patterns of neural activation while

reading, this would suggest that the neurodevelopmental changes underlying successful reading development are not susceptible to experience-driven changes.

METHODS

Participants

Thirty-two typically developing right-handed monolingual and bilingual children (mean age = 8.6, *SD* = 0.9) and 16 monolingual and bilingual adults participated in this study (mean age = 17.8, *SD* = 0.8). Children were further subdivided into two groups: younger readers and older readers. Younger readers were grade 1 and 2 students between the ages of 6 and 8.5. Older readers were grade 3 and 4 students between the ages of 8.5 and 10. Thus, the study design contained six groups (eight participants per/group): younger monolingual readers, older monolingual readers, adult monolingual readers, younger bilingual readers, older bilingual readers, and adult bilingual readers (see the summary of participant information in Table 1).

All participants were native speakers of English and had begun acquiring this language from birth. All bilingual participants were exposed to their two languages from birth. As a specific design feature of this study, bilingual participants spoke languages from a varied linguistic pool. These languages included Cantonese and Mandarin (6 participants), Hakka (1 participant), Arabic (1 participant), Vietnamese (3 participants), Tamil (3 participants), Urdu (2 participants), Punjabi (2 participants), Spanish (1 participant), Russian (1 participant), and French (4 participants). We specifically selected bilingual participants that would yield language pairs from typologically distinct languages covering analytical languages (e.g., English), morphologically rich languages (e.g., Russian, Spanish, Urdu), different writing systems (e.g., Cyrillic), and word orders (e.g., SVO [Russian], SOV [Punjabi]). This permitted us to directly compare monolingual versus bilingual brains. If we had only compared, for example, English–Spanish bilinguals to English monolinguals, we incurred the risk of observing group differences that could be attributable

TABLE 1
Participant Information

| <i>Group/Age</i> | <i>Age at Testing</i> | <i>Grade at Testing</i> | <i>SES</i> |
|------------------|-----------------------|-------------------------|------------------|
| | <i>Mean (SD)</i> | <i>Mean (SD)</i> | <i>Mean (SD)</i> |
| Monolinguals | | | |
| Early Readers | 7.7 (0.5) | 1.9 (0.4) | 3.4 (0.8) |
| Skilled Readers | 9.3 (0.4) | 3.6 (0.5) | 3.0 (0.8) |
| Adults | 18.9 (0.8) | n/a | n/a |
| Bilinguals | | | |
| Early Readers | 7.6 (0.5) | 1.6 (0.5) | 3.0 (0.8) |
| Skilled Readers | 9.2 (0.4) | 3.3 (0.5) | 2.6 (1.4) |
| Adults | 18.6 (0.7) | n/a | n/a |

Note. SES = socioeconomic status.

to only English–Spanish bilinguals and English monolinguals, and not be generalizable to all bilinguals. Hence, our study design controlled for these potential confounds.

Exclusion criteria for participants consisted of speech/language disorders, reading disabilities, developmental delays, or any other neurological condition, as indicated in the parent report. We used the parent report to ascertain that our sample was comprised of typically developing children. Children with significant vision or hearing problems that would interfere with their ability to participate were also excluded, as indicated in the parent report. All adult participants reported being right-handed. Parents reported the hand preferences of their children. All participants were living in Toronto, Canada at the time of testing. Data from child participants were collected during the summer vacation (June–August), thus any differences in reading skill could not be attributed to time of formal education during the school year. The parents received monetary compensation for their travel and adult participants received credit towards their first-year psychology course for their participation in the study. This study received ethical approval from the research ethics review board at the University of Toronto.

Participant Screening

Assessment of bilingual language background and use. Parents and adult participants filled in a standardized assessment tool, the “Bilingual Language Background and Use Questionnaire” (BLBUQ; for more details on this extensive bilingual language questionnaire see Holowka, Brosseau-Lapr e, & Petitto, 2002; Kovelman et al., 2008a; 2008b; Penhune, Cismaru, Dorsaint-Pierre, Petitto, & Zatorre, 2003; Petitto et al., 2001; 2012; Petitto, Zatorre, et al., 2000). Adult participants completed the adult version and parents filled out the child version of the BLBUQ. This questionnaire asked (a) detailed questions about parents’ language use and attitudes (language background, educational history, employment facts, social contexts across which each parent uses his or her languages, personal language preference containing standardized questions to assess language dominance and language preference, personal attitudes about language/s, language use with the child and participant’s other siblings, parents’ linguistic expectations for their child, parents’ attitudes towards bilingualism, parents’ self-assessment about “balanced” bilingual input) and (b) detailed questions about the nature of language input, languages used with the child, questions about child rearing, questions about who cares for the child and number of hours, caretaker’s language/s, and child’s exposure patterns to television/radio. Participants were grouped as monolinguals or bilinguals based on the age of first bilingual exposure and the relative amount of exposure in each language. This screening tool gave us confidence in our monolingual and bilingual group assignments.

Socioeconomic status. All children were similar in socioeconomic status (SES) as indexed by maternal education and occupation (Hoff, 2013). SES was coded on a scale of one through four based on the following: upper-SES = professionals with “college graduate,” upper-middle-SES = service sector workers with “college graduate,” middle-SES = service sector with “high school/GED” and blue collar workers with “college graduate,” and lower-SES = blue collar workers with “high school/GED.” Mean SES rank for younger monolingual readers, younger bilingual readers, older monolingual readers, and older bilingual readers were not significantly different ($F(3,23) = .765, p > .05$; see Table 1).

Experimental Procedures and Stimuli

While undergoing fNIRS neuroimaging, participants were presented with a single-word reading task in English (bilinguals only completed the task in one language). Word stimuli were used from the widely known Woodcock Johnson Language Proficiency Battery–Revised (Woodcock, 1991) and were previously published (Kovelman et al., 2008a; Berens, Kovelman & Petitto, 2013). All participants were presented with 72 words divided into three conditions: regularly spelled (e.g., *stop*), irregularly spelled (e.g., *debt*), and pronounceable but nonexistent nonsense words (e.g., *dask*). The word frequencies for all stimuli were controlled and words varied from 3–7 letters in length, this was maintained across different word types (regular, irregular, and nonsense).

A block design comprised of three runs was used to examine neural activation during word reading. Runs began with 30 seconds of fixation, a set of instructions that reminded participants to read each word out loud. Each run included a block of 8 regular words, a block of 8 irregular words, and a block of 8 nonsense words, with a 2-second rest break fixation between each stimulus, and 15-second rest break fixation between each block. The participant was seated in a chair facing a computer monitor. A microphone to record participants' responses was located approximately 30 cm from their face. Single word stimuli appeared on a computer monitor and participants were required to read the word aloud into the microphone. The length of stimulus presentation depended on participants reading time, which was measured from the onset of their utterance. The entire experiment was approximately 15 minutes (Shalinsky, Kovelman, Berens, & Petitto, 2009).

fNIRS brain imaging. Similar to fMRI, fNIRS measures changes in blood oxygenation levels; however, fNIRS has important advantages over fMRI. fNIRS has a faster sampling rate of neural activity at 10 Hz, as compared to fMRI's sampling rate of \sim once every 2 seconds. Thus, fNIRS is considered as a closer measure of neural activity than the fMRI. fNIRS yields separate measures of deoxygenated and oxygenated hemoglobin in “real time” during recording, compared to fMRI which yields a combined blood oxygen level density (BOLD) measure (a ratio between oxygenated and deoxygenated hemoglobin). fNIRS has good spatial resolution and it has better temporal resolution than fMRI (\sim <5 s hemodynamic response, HR). fNIRS' depth of recording in the human cortex is less than fMRI, measuring about \sim 3 to 4 cm deep, but this is well-suited for studying the brain's higher cortical functions, such as language.

The hemodynamic response was measured with a Hitachi ETG-4000 Near Infrared Spectroscopy system with 46 channels, acquiring data at 10 Hz. The 18 lasers and 15 detectors were segregated into one 3×5 array and two 3×3 arrays. Once the participant was comfortably seated, one array was placed on each side of the participant's head and one array was placed over top. Positioning of the array was accomplished using the 10–20 system (Jasper, 1958; Shalinsky et al., 2009) to maximally overlay regions classically involved in language areas in the left hemisphere as well as their homologues in the right hemisphere, and attentional and executive functioning areas in the frontal lobe. Participants with all hair types and colors were included in the study and great care was taken to move aside hair from under the probe emitters and detectors to ensure good contact with the scalp. Once the probe array was positioned on the participants' head, black cloth caps were placed over the probe array to block any ambient light from interfering with NIRS measurements. The experiment took place in a dimly lit room to further ensure no light interference with NIRS measurements.

Source localization. The spatial registration of NIRS channel to neuroanatomical structures in MNI space was ensured using several procedures. First, the NIRS optode array was carefully positioned on the participant's head according to internationally established scalp positions using the 10–20 system (Jasper, 1958). Second, we recorded the three-dimensional coordinates of each optode and detector in our probe array as well as relevant 10–20 system scalp locations using a three dimensional digitizer (Polhemus Corp.). These measurements were used to establish the scalp location of each NIRS channels (located between adjacent optodes and detectors). Next, we applied spatial localization algorithms that have previously been shown to reliably make inferences about underlying neuroanatomical structures in the absence of a structural MRI (Singh, Okamoto, Dan, Jurcak, & Dan, 2005). Singh et al.'s (2005) procedure uses known standard deviations in probabilistic registration of fNIRS data to structural MRI images to register three dimensional scalp positions to MNI space. MRI co-registration with fNIRS channels was previously accomplished by having participants wear an identical optode array holder, but with vitamin E capsules, while undergoing a structural MRI scan (Kovelman et al., 2008). The lipid content of vitamin E capsules displays on a structural MRI and indicates the neural structures that correspond to NIRS channels. MRI co-registration remains the ideal solution to establishing source localization, particularly given the variability in the development of neuroanatomical structures in a pediatric population.

Data Analysis

fNIRS data pre-processing. Using the modified Beer–Lambert equation, optical density values were converted into concentration changes in oxygenated and deoxygenated hemoglobin response (HbO and HbR, respectively; Shalinsky et al., 2009). Changes in HbO and HbR concentrations were filtered with a Gaussian filter and decomposed using a Wavelet-Minimum Description Length (MDL) detrending algorithm in order to remove global trends resulting from breathing, blood pressure variation, vasomotion, or participant movement artifacts and improve the signal-to-noise ratio (Jang et al., 2009).

Statistical analysis. Innovative and complementary statistical techniques were used here for the first-time to provide new insights into neurodevelopmental changes. We combined Statistical Parametric Mapping with Partial Least Squares analysis, a multivariate statistical approach, to reveal differences in the patterns of neural activation in monolingual and bilingual brains across time, providing a powerful lens into the present questions.

Statistical Parametric Mapping for NIRS (NIRS-SPM) analysis. First, data were analyzed using a Matlab-based statistical software package: Statistical Parametric Mapping for NIRS (NIRS-SPM, Version 3.1) (Jang et al., 2009; Ye, Tak, Jang, Jung, & Jang, 2009). NIRS-SPM calculates activation maps of HbO, HbR, and THb based on the general linear model and Sun's tube formula correction (Sun, 1993). The HbO values were used in all subsequent analyses comparing regular, irregular, nonsense, and baseline conditions (for detailed methods see especially, Kovelman, Shalinsky, White, Schmitt, Berens, & Petitto, 2009).

Partial Least Squares (PLS) analysis. PLS is a multivariate data analysis technique that allows for the simultaneous analysis of spatial and temporal neuroimaging data (McIntosh,

Bookstein, Haxby & Grady, 1996). This approach is ideal for highly correlated dependent measures, as is the case for neuroimaging data sets. Individual data points in fNIRS data matrices are both temporally and spatially correlated; that is, data points are partially dependent on the values of adjacent data points in time, as well as data points belonging to the same channel and adjacent brain regions. In PLS, the optimal least-squares fit to a part of a covariance matrix is calculated. That is, PLS calculates the covariance of two or more matrices (e.g., a neuroimaging data matrix and a design matrix) with the goal of obtaining a new set of variables that best relate the two matrices using the fewest dimensions (McIntosh et al., 1996).

PLS analysis began with a data matrix composed of rows of data representing changes in oxygen concentrations at 20 time points following stimulus presentation (corresponding to 2 seconds), at each channel, for each subject, blocked by condition. Individual data matrices were constructed per group. Each matrix is made of a priori sub-matrices that code for different aspects of the experimental design. Mean-centered task PLS approach was used to analyze group differences (McIntosh et al., 1996). In the mean-centered approach, the average for each condition is calculated, and the mean of each column in the resulting matrix is subtracted from each value.

The covariance of each time point for each channel with each condition is calculated and the resulting covariance matrix is subjected to singular value decomposition (SVD). The decomposition yields a set of mutually orthogonal latent variables (LVs), each consisting of a Brain Score indicating the location and timing of the task effects across conditions and subjects, and a Design Score indicating the task contrast (McIntosh et al., 1996). Each LV expresses a symmetrical relationship between the components of the experimental design that relate to the measures of changes in oxygen concentrations, and the optimal spatiotemporal pattern of changes in oxygen concentrations related to the design components. Channel saliences, which are the numerical weights at each time point and channel location, identify the time points that are most related to the task effects expressed in the LV. Design saliences indicate the extent to which each contrast is related to the pattern of changes in oxygen concentrations. Brain scores are the dot product of a subject's measured changes in oxygen concentrations and the channel saliences for a given LV, and indicate how strongly individual subjects express the patterns on the LV.

Statistical inferences regarding the number of LVs to retain are implemented using permutation tests and bootstrapping. Bootstrap ratios of 2.57 are roughly equivalent to a *z*-score with probability 0.01. 1000 permutation tests of the LVs were performed to address whether the effect represented by the given LV is statistically different from noise. One thousand bootstrap samples were performed to estimate the standard errors of the saliences. The ratio of the salience to the bootstrap standard error is used to determine what portion of the fNIRS signal shows the experimental effect across subjects.

RESULTS

Behavioral Results

We asked whether younger and older monolingual and bilingual readers show different or similar reading response times and accuracy rates across word types (Regular, Irregular, and Nonsense Words). We performed a $2 \times 3 \times 3$ (Group \times Age \times Word Type) repeated measures ANOVA.

Response Time

This analysis revealed a main effect of Word Type (Regular, Irregular, and Nonsense Words; $F(2,42) = 71.394, p < .001$, partial $\eta^2 = .630, \omega^2 = 0.524$) and a main effect of Age (Younger Reader, Older Reader, and Adult; $F(2,42) = 9.770, p < .001$, partial $\eta^2 = .318, \omega^2 = 0.014$). There was no main effect of Group (Monolingual and Bilingual; $F(1,42) = .015, p > .05$, n.s.). Overall, all participants demonstrated significantly faster response times for regular words, followed by irregular words, with the slowest response times for nonsense words (see Table 2). Adults demonstrated faster response times relative to children, with children who were older readers demonstrating faster response times relative to younger readers. Further, significant Word Type \times Group interactions were observed ($F(2,42) = 5.179, p < .01$, partial $\eta^2 = .110, \omega^2 = 0.031$) and Word Type \times Age ($F(4,42) = 5.789, p < .001$, partial $\eta^2 = .216, \omega^2 = 0.071$). Younger readers, both monolingual and bilingual, demonstrated faster response times to regular relative to irregular words; however, children who were older readers and adults did not demonstrate significant differences between regular and irregular words. All participants demonstrated faster response times for regular and irregular words relative to nonsense words with the exception of younger bilingual readers, who did not demonstrate significant differences between irregular and nonsense words.

Accuracy

This analysis revealed a main effect of Word Type (Regular, Irregular, and Nonsense Words; $F(2,84) = 38.167, p < .001$, partial $\eta^2 = .476, \omega^2 = 0.357$) and a main effect of Age (Younger Reader, Older Reader, and Adult; $F(2,42) = 21.083, p < .001$, partial $\eta^2 = .501, \omega^2 = 0.010$). There was no main effect of Group (Monolingual and Bilingual; $F(1,42) = .030, p > .05$, n.s.). Overall, participants demonstrated significantly higher accuracy for regular relative to irregular and nonsense words but did not demonstrate significant differences between irregular and nonsense words (see Table 2). Adults demonstrated higher accuracy relative to children, with

TABLE 2
Group Response Latency and Accuracy for Regular, Irregular, and Nonsense Word Conditions

| Language Group | Response Latency | | | % Response Accuracy | | |
|-----------------|------------------|----------------|----------------|---------------------|-------------|-------------|
| | Mean (SD) | | | Mean (SD) | | |
| | Regular | Irregular | Nonsense | Regular | Irregular | Nonsense |
| Monolinguals | 931.6 (223.2) | 976.7 (245.1) | 1200.7 (295.6) | 93.5 (10.9) | 84.5 (19.2) | 80.1 (20.2) |
| Younger Readers | 1061.9 (271.3) | 1144.1 (249) | 1347.8 (175.2) | 83.8 (14.5) | 65 (20.8) | 65.7 (19.9) |
| Older Readers | 947.9 (150.1) | 1017.1 (169.6) | 1327.1 (316.8) | 96.7 (3.9) | 89 (5.5) | 78.9 (19.5) |
| Adult Readers | 784.9 (152.5) | 768.8 (152.7) | 927.2 (166.3) | 100 (0) | 99.5 (5.7) | 95.8 (6.7) |
| Bilinguals | 920.7 (200.8) | 1020 (299.1) | 1126.3 (285.6) | 96.1 (6.7) | 82.1 (16.4) | 88.5 (11.1) |
| Younger Readers | 1062.3 (279.9) | 1273.1 (395.2) | 1213.3 (356.9) | 90.5 (8.9) | 66.8 (13.8) | 80.9 (15.2) |
| Older Readers | 912.8 (155.9) | 973.4 (205.4) | 1186.9 (301.5) | 98.4 (3.1) | 84.9 (13.8) | 88.7 (5.9) |
| Adult Readers | 805.6 (48.1) | 851 (110.8) | 982.1 (137.7) | 99.5 (1.5) | 94.8 (6.6) | 95.8 (3.2) |

children who were older readers demonstrating higher accuracy relative to children who were younger readers. Further, significant Word Type \times Group interactions were observed ($F(2,84) = 6.702$, $p < .01$, partial $\eta^2 = .138$, $\omega^2 = 0.054$) and Word Type \times Age ($F(4,84) = 7.914$, $p < .001$, partial $\eta^2 = .274$, $\omega^2 = 0.134$). All children demonstrated higher accuracy for regular relative to irregular and nonsense words but did not demonstrate significant differences between irregular and nonsense words with the exception of younger bilingual readers; they demonstrated higher accuracy for nonsense relative to irregular words. Monolingual adults did not demonstrate significant differences between regular, irregular or nonsense words. Bilingual adults did not demonstrate significant differences between regular and irregular words and irregular and nonsense words, but did demonstrate *higher* accuracy for regular relative to nonsense words.

Neuroimaging Results

With the goal of identifying brain sites and systems and their neurodevelopmental change over time (questions 1 & 2), we first examined the pattern of neural activation across the three word types (Regular, Irregular and Nonsense words) in children who were younger readers, children who were older readers, and adult readers. We observed age-related differences in neural activation while reading regular, irregular, and nonsense words. Younger readers showed minimal differences in neural activation between irregular and regular words, demonstrating robust neural recruitment of the left STG for both word types. However, children who were older readers showed more robust (greater) neural activation of the LIFG for irregular relative to regular words, and more robust neural activation in the angular gyrus and supramarginal gyrus of the IPL for regular relative to irregular words (see Figure 1). Further, younger readers showed greater neural activation for regular words relative to nonsense words in the bilateral IPL, whereas children

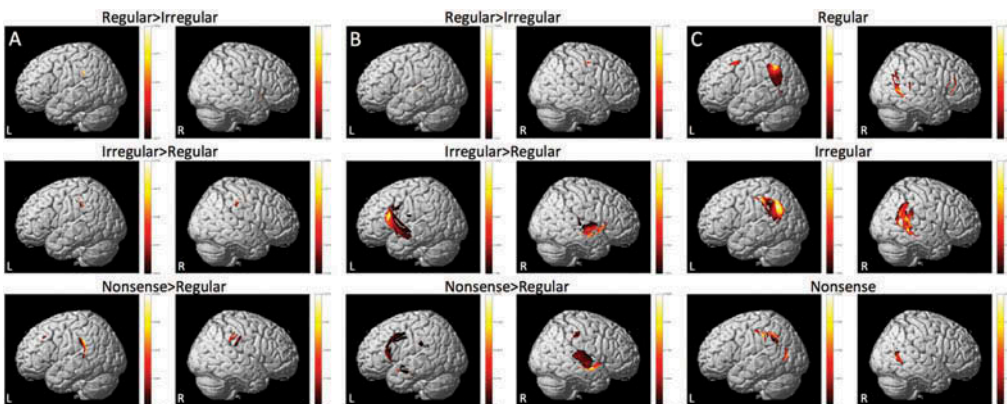


FIGURE 1 Neural activation of younger readers, older readers, and adult readers (t -statistic map from HbO). (a) Younger readers' neural activation for regular > irregular, irregular > regular, and nonsense > regular word types. (b) Older readers' neural activation for regular > irregular, irregular > regular, and nonsense > regular word types. (c) Adult > child neural activation for regular, irregular, and nonsense word types.

who were older readers showed greater neural activation for nonsense words relative to regular words in the left IFG, and bilateral STG and IPL (see Figure 1). Adults demonstrated greater neural activation relative to children across all word types in the bilateral IPL, whereas all children demonstrated greater neural activation relative to adults in the left middle temporal gyrus (MTG) (see Figure 1).

PLS analysis was performed across the two groups, younger and older readers, and across all conditions, regular, irregular, and nonsense words. One LV was significant by permutation test ($p = .005$) and accounted for 67.9% of the cross-block covariance matrix. The remaining five LVs accounted for the remaining variance and were not significant. Plots of the brain scores by design scores and task saliences for LV1 indicate that older readers demonstrated greater decreases in oxygenated hemoglobin for irregular and nonsense relative to regular words, whereas younger readers demonstrated more comparable neural activation across word conditions (see Figure 2).

To understand whether early life language experience influenced the neural systems underlying reading and their neurodevelopmental change over time (question 3), we compared the pattern of neural activation in monolingual and bilingual participants across the three word types and across development. We observed differences in neural activation among monolingual and bilingual participants. Younger monolingual readers showed more robust neural activation in the left IFG while reading irregular words relative to younger bilingual readers. However, younger bilingual readers showed more robust neural activation in the left STG, left DLPFC and rostralateral prefrontal cortex (RLPFC) while reading regular words, the left RLPFC, and bilateral STG and IPL while reading irregular words, and the left STG, left DLPFC, and right IPL while reading nonsense words relative to younger monolingual readers (see Figure 3). Older bilingual readers showed more robust neural activation in left and right hemisphere classic language areas and the prefrontal cortex including the left IFG, left MTG, left DLPFC, right RLPFC, right STG and right IPL while reading regular words, and left DLPFC and RLPFC, bilateral IFG while reading irregular and nonsense words relative to older monolingual readers (see Figure 3). Older monolingual readers did not show any significantly greater neural activation across all

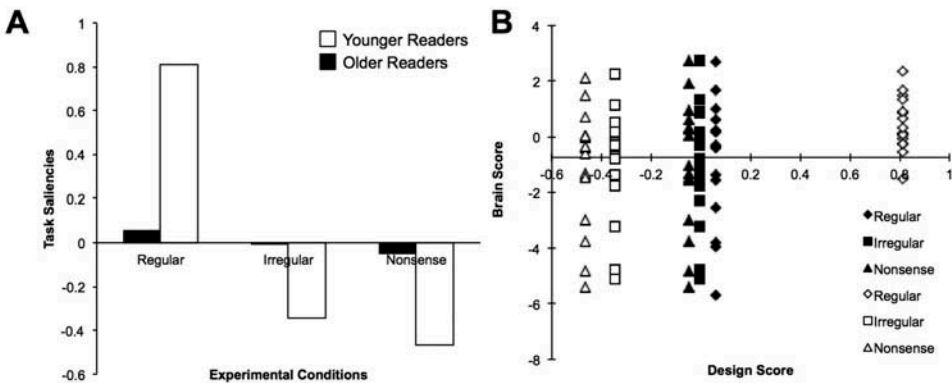


FIGURE 2 (a) Task saliences for LV1 and (b) plot of brain scores by design scores for younger and older readers.

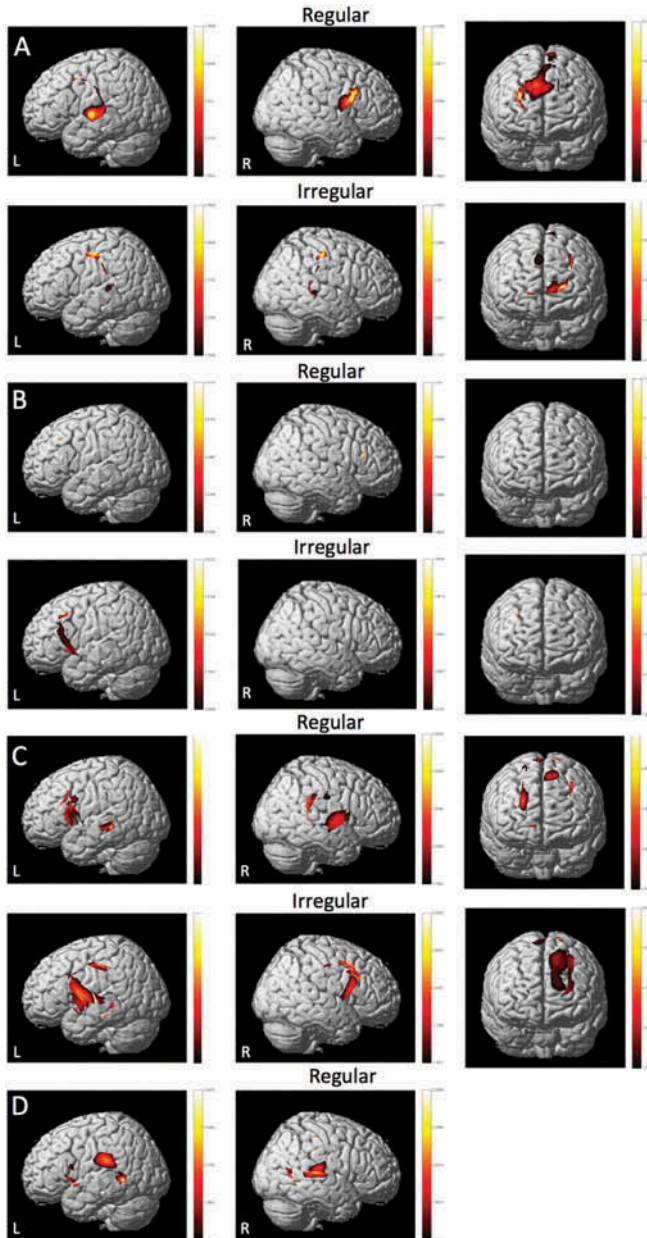


FIGURE 3 Neural activation of monolingual and bilingual readers (*t*-statistic map from HbO). (a) Younger bilinguals > younger monolinguals' neural activation for regular and irregular word types. (b) Younger monolinguals > younger bilinguals' neural activation for regular and irregular word types. (c) Older bilinguals > older monolinguals' neural activation for regular and irregular word types. (d) Adult bilinguals > adult monolinguals' neural activation for regular word type.

word types relative to bilinguals. Bilingual adult readers showed more robust neural activation in the left IFG and bilateral STG while reading regular words relative to monolingual adult readers (see Figure 3).

PLS analysis was performed across two groups, monolingual and bilingual children, and across all conditions, regular, irregular and nonsense words. One LV was significant by permutation test ($p < .001$) and accounted for 88.3% of the cross-block covariance matrix. The remaining five LVs accounted for the remaining variance and were not significant. Plots of the brain scores by design scores for LV1 indicate that monolingual readers demonstrated greater decreases in oxygenated hemoglobin for nonsense relative to regular and irregular words, whereas bilingual readers demonstrated greater decreases in oxygenated hemoglobin for regular and irregular words relative to nonsense words (see Figure 4). Channels maximally overlaying right IFG, bilateral STG and IPL, bilateral DLPFC and RLPFC area, and right Pre-Central and Post-Central Gyrii most reliably expressed the differences between monolingual and bilingual readers as indicated by high bootstrap ratios (at or above 2.57 indicating significance at 0.01; see Figure 4). Across these channels, bilinguals show greater increase in oxygenated hemoglobin relative to monolinguals.

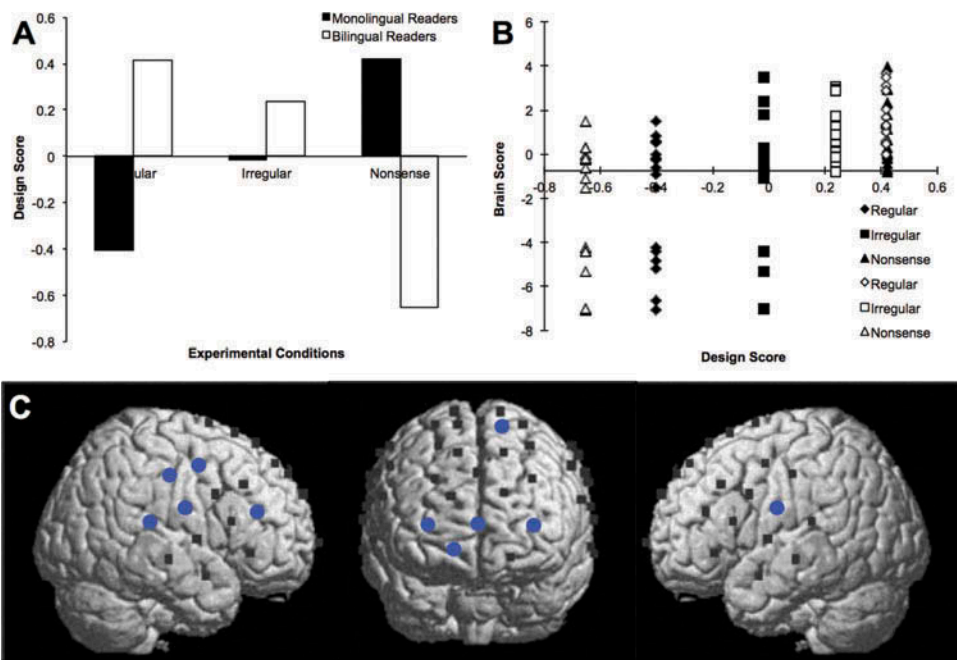


FIGURE 4 (a) Task saliencies for LV1 and (b) plot of brain scores by design scores for monolingual and bilingual readers. (c) Location of Near Infrared Spectroscopy (NIRS) channels that most reliably express differences between monolingual and bilingual readers.

DISCUSSION

An innovative goal of the present study was to identify the brain sites and systems that underlie early reading and the neurodevelopmental changes that support successful reading acquisition across younger children, older children, and adults. Another goal was to advance understanding of whether differences in early life language experience can impact the neural systems and their maturation that underlie reading through the novel lens of monolingual and bilingual brains. Here we asked do differences in early life language experience (bilingual versus monolingual) impact developmental changes in patterns of neural activity in classic language and cognitive brain regions during reading?

We examined both the behavior (response latency and accuracy) and the pattern of neural activation in monolingual and bilingual younger readers, older readers, and adult readers across three word reading conditions (regular, irregular, and nonsense words). Regular and nonsense words have a one-to-one grapheme-to-phoneme correspondence, whereas irregular words do not. Recall that a grapheme-to-phoneme correspondence strategy will result in the correct reading of regularly spelled word and a nonsense word; this strategy fails for irregularly spelled words. On the other hand, a whole-word strategy would yield correct reading for both regularly spelled and irregularly spelled words. This specific design feature permitted us to examine the neural resources that support early reading skills, which rely predominantly on a grapheme-to-phoneme correspondence strategy, as well as later reading skills, which instead rely more on whole-word reading strategy. These words exploited differences in neural processing underlying reading and allowed us to test our two hypotheses.

Our behavioral results revealed that younger and older readers show differences in reading response latency and accuracy across the three word types. Younger readers demonstrated faster response times for regular relative to irregular words; however, older readers and adults demonstrated no differences in response times to regular and irregular words. All children also demonstrated higher accuracy rates for regular relative to irregular words, whereas adults demonstrated no differences in accuracy rates for regular and irregular words. This finding is predicted from a developmental difference in reading skill. A whole-word reading strategy yielded comparable performance across regular and irregular word types in older readers; however, a phoneme-to-grapheme correspondence strategy used by younger readers yielded better reading performance only for regularly spelled words.

Our neuroimaging results were especially revealing regarding the neural sites and systems that support the behavioral findings and their neurodevelopmental changes over time. Younger readers showed similar neural recruitment of the STG for both irregular and regular words; however, older readers showed robust neural recruitment of the left IFG for irregular relative to regular words and more robust neural recruitment of the IPL for regular relative to irregular words. It is here that we observed a focal brain correlate of a developmental reading milestone: Younger readers show robust neural activation in phonological processing tissue at an age when children rely heavily on matching phonological information onto word orthography. By contrast, older readers show robust neural activation in tissue classically associated with lexical access, morphology, and syntax at an age when children rely more heavily on processing the word as a whole; moreover, this neural activation is greater for irregularly spelled words, which require a whole-word reading approach.

Commensurate with Hyp 1, we found that early life language experience (monolingual vs. bilingual) impacts the developmental shift in neural activation observed above. It is also here that we see the new perspective that neuroimaging data can provide beyond behavioral observations alone: Although we found no overall behavioral difference in response times and accuracy rates between monolingual and bilingual readers, we *did* find important differences between monolingual and bilingual brains, suggesting that language experience can modify the neurodevelopmental changes that support reading.

Across all age groups, an overall neural pattern emerged. Bilinguals showed more robust recruitment of the left IFG, left STG, and left IPL and the right hemisphere homologues of these classic left hemisphere language areas, as well as, the DLPFC and RLPFC relative to monolinguals. That bilingual readers show increased activation in the STG is consistent with the demands of processing two phonological systems over one, that is, bilinguals may recruit a greater extent and variability of the left STG and additional right hemisphere homologues for phonological processing (Kovelman et al., 2008b). This neural difference may provide the bilinguals with a phonological advantage. Indeed, experience with two language systems (bilingual), specifically two phonologies, instead of one (monolingual), has been shown to result in a phonological processing advantage (Petitto et al., 2012) and a reading advantage (Kovelman et al., 2008a).

Furthermore, bilinguals showed more variability in neural activation throughout the prefrontal cortex including the RLPFC and DLPFC. The RLPFC is involved in reasoning and integrating information (Gilbert et al., 2006) and the DLPFC is involved in working memory and attention (Balconi, 2013; Fuster, 2008), which is consistent with monitoring and selecting between two language systems and the demands of a complex task such as reading.

CONCLUSION

Surprising advances to our understanding of the brain's systems underlying reading in early life were laid bare in the present study. Two predominant patterns of change in brain activation while reading were revealed: younger readers showed more robust recruitment of phonological processing tissue (STG) while reading, but older readers showed more robust recruitment of tissue associated with lexical access, morphology, and syntax (LIFG). This age-related shift in the brain's recruitment of classic language areas for reading indicates a greater neural sensitivity to the sound patterns of words in younger readers and greater neural sensitivity to the whole word in older readers.

To be sure, the present study revealed new insights into the impact of early life language experience on developmental changes in brain activity over time that may lead to reading advantages. Both monolingual and bilingual children showed a neurodevelopmental shift in the recruitment of classic language areas during reading, with more robust activation in the STG among younger readers and more robust activation in the LIFG among older readers. However, a neural difference was observed between monolingual and bilingual readers, providing insight into the extent with which this neurodevelopmental shift is malleable by early life experience. Bilingual readers showed a greater extent and variability of neural activation in bilateral classic language (LIFG, STG, IPL) and higher cognitive (DLPFC, RLPFC) brain areas, suggesting that bilingualism may lead to enhanced linguistic and cognitive processing. This "neural signature" (Kovelman et al.,

2008b) reveals the extent of neural architecture underlying language and reading that can be modified through early life language experience and may have important implications for how a bilingual child most optimally learns to read. What the behavioral studies alone can not reveal—indeed a first here—are focal brain correlates of developmental reading milestones, which are maturational controlled, and that therefore can shed new and adjudicating light on controversies in reading acquisition that hitherto had become largely philosophical in stance.

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