Published in final edited form as:

Brain Lang. 2015 April ; 143: 11–19. doi:10.1016/j.bandl.2015.01.010.

Neural Correlates of Single Word Reading in Bilingual Children and Adults

Arturo E. Hernandez^{a,*}, Elizabeth A. Woods^a, and Kailyn A. L. Bradley^a

^aDepartment of Psychology, University of Houston

Abstract

The present study compared the neural correlates of language processing in children and adult Spanish-English bilinguals. Participants were asked to perform a visual lexical processing task in both Spanish and English while being scanned with fMRI. Both children and adults recruited a similar network of left hemisphere “language” areas and showed similar proficiency profiles in Spanish. In terms of behavior, adults showed better language proficiency in English relative to children. Furthermore, neural activity in adults was observed in the bilateral MTG. Age-related differences were observed in Spanish in the right MTG. The current results confirm the presence of neural activity in a set of left hemisphere areas in both adult and child bilinguals when reading words in each language. They also reveal that differences in neural activity are not entirely driven by changes in language proficiency during visual word processing. This indicates that both skill development and age can play a role in brain activity seen across development.

Keywords

bilingual language acquisition; lexical processing; human development; cognitive neuroscience

1. INTRODUCTION

The processing of lexical items in monolinguals has been thought to rely on a left-lateralized network that involves visual association areas such as the fusiform gyrus (FG) for orthographic processing, auditory association areas such as the superior temporal gyrus (STG) for phonological processing, amodal association areas such as the middle temporal gyrus (MTG) for semantic processing, and heteromodal areas in inferior parietal lobule (IPL) for mapping between these different representational systems. Posterior language-processing areas are also thought to be highly connected with anterior systems such as the inferior frontal gyrus (IFG), responsible for more detailed semantic and phonological processing (Bitan et al., 2007; Bolger et al., 2008; Booth et al., 2006; Booth, 2007; Price 2000; Pugh et al., 2000 Turkeltaub et al., 2002). However, to date, studies of language development have not examined the nature of lexical processing in early second language learners. The current study is designed to fill this gap by investigating the neural correlates

*Corresponding author: University of Houston, Department of Psychology, 126 Heyne Building, Houston, Texas, 77204-5022, aehernandez@uh.edu Telephone: 713-743-8354, Fax: 713-743-8588.

of visual word processing in bilingual children and adults who acquired their second language early in childhood.

1.1. Neural Development of Lexical Processing in Monolinguals

Neuroimaging studies of language acquisition in monolingual populations have revealed increases in activation in most of the aforementioned regions including the MTG (Chou et al., 2006; Turkeltaub et al., 2002), IPL (Booth et al., 2008; Chou et al., 2006) and IFG (Booth et al., 2004; Cone et al., 2008; Gaillard et al., 2003; Holland et al., 2001; Shaywitz et al., 2002; Turkeltaub et al., 2002), as a function of increased skill and development. The opposite comparison, which looks at increased activity in children relative to adults has been observed in the right hemisphere. Relative to adults, children tended to activate to a greater extent right IFG in spelling and reading tasks (Booth et al., 2004; Turkeltaub et al., 2002), as well as right STG for semantic judgment of visual words. In addition, decreased activation in right MTG has been associated with decreased skill on semantic judgment of visual words. These results suggest increasing specialization and left lateralization across language development (Holland et al., 2001; Johnson, 2011).

1.2. Neural Correlates of Second Language Processing

Although models of lexical processing in monolinguals as outlined above are relatively well-established, additional questions have been raised about language processing and neural organization in those who speak more than one language. The current consensus is that both first (L1) and second language (L2) processing rely on common cortical areas with slight variability occurring due to several factors, including age of acquisition (AOA), proficiency, and amount of exposure (Hernandez & Li, 2007; Perani & Abutalebi, 2005; Tatsuno & Sakai, 2005). However, functional magnetic resonance imaging (fMRI) studies regarding lexical processing in bilinguals have primarily considered cross-language differences in adults (Chee et al., 1999; Das, et al., 2011; Jamal et al., 2011; Li, 2009; Meschyan & Hernandez, 2006; Nakamura et al., 2010; Tan et al., 2003) with relatively few studies of bilingual children (Tan et al., 2011; Xue et al., 2004).

To our knowledge the only study that has investigated the brain activity associated with both child and adult bilinguals was conducted by Archila-Suerte et al. (2012). In that study, a group of child and adult sequential Spanish-English bilinguals were asked to listen to pairs of sounds that differed by a single vowel. A group of children between the ages of 6–7, 8–10, and a group of adults ages 18–24 were asked to listen to a series of single syllables consisting of two consonants and a vowel. A control group of monolinguals was also tested across all the age ranges. Bilingual children between the ages of 6–7 showed strong activity in bilateral STG, a pattern present in both monolingual adults and children. Unlike monolinguals, however, bilinguals' pattern of brain activity differed in the older group of children. There was significantly more activity in children aged 8–10, in areas that are involved in cognitive control, including bilateral activity in the inferior parietal lobe and the middle frontal gyrus. These differences diminished in bilingual adults, resulting in activity mostly in bilateral STG. These results suggest that bilinguals' processing of nonsense syllables in English shows a developmental trend that differs significantly from

monolinguals. The current study seeks to expand on this by looking at the nature of word reading in both languages in a very similar population.

1.3. Current Study

Behavioral studies with early L2 learners have revealed an interesting shift in proficiency across development. Specifically, early L2 acquisition can lead to a shift from L1 dominance in childhood to L2 dominance by adulthood, with the shift occurring as early as age 8 to 13 years (Kohnert, Bates, & Hernandez, 1999; Meschyan & Hernandez, 2006). The aim of the present study was to examine the neural correlates of lexical processing in early L2 learners during this transition from L1 dominance in childhood to L2 dominance in adulthood, using a single-word reading task in both languages. Although children and adults were expected to recruit a similar network of occipitotemporal, temporoparietal, and frontal cortices, skill and developmental differences were also expected. Specifically, adults were expected to be more proficient and skilled than children at processing L2 (Kohnert et al., 1999). As such, adults were expected to show greater activation than children in brain regions previously reported to increase as a function of skill and development, including the left MTG, IPL, and IFG (Booth et al., 2004; Chou et al., 2006; Cone et al., 2008; Gaillard et al., 2003; Holland et al., 2001; Shaywitz et al., 2002; Turkeltaub et al., 2002). Due to their potentially lower skills, children were expected to recruit similar cortical regions as adults but to a lesser extent, as well as possible additional right hemisphere homologues. Finally, language proficiency should modulate this effect such that age-related differences would be larger in English, the second language, than in Spanish, the first language.

2. METHOD

2.1. Participants

Participants were forty-one right-handed individuals, 20 adults and 21 children, from the Houston area. Adults were 18 – 26 years old ($M = 21.55$, $SD = 2.14$), and children were 8 – 13 years old ($M = 10.52$, $SD = 1.57$), $F(1, 39) = 356.65$, $p < .0001$. All participants were native speakers of Spanish who learned English before the age of 9 years. Adults and children did not have a significantly different AOA for English (adults $M = 3.95$, $SD = 2.17$; children $M = 3.67$, $SD = 1.20$), $F(1, 39) = .262$, $p = .612$. However, adults and children significantly differed in the percentage of their day that they spoke English (adults $M = 73.50$, $SD = 15.40$; children $M = 54.76$, $SD = 18.34$), $F(1, 39) = 12.49$, $p = .001$ and Spanish (adults $M = 28.25$, $SD = 15.41$; children $M = 45.24$, $SD = 18.33$), $F(1, 39) = 10.26$, $p = .003$. Demographic information is summarized in Table 1. Experimental procedures were approved by a Human Subjects Committee and written informed consent was obtained from all participants and legal guardians of minors.

2.2. Task and Procedures

After giving consent, participants were screened for handedness, claustrophobia, history of neurological, psychiatric, and learning disorders, language history, and presence of metal in the body. Participants' English and Spanish proficiency was also measured using the picture vocabulary (WLPB-PV) and listening comprehension (WLPB-LC) subtests of the

Woodcock Language Proficiency Battery Revised (Woodcock, 1991). A composite proficiency score was calculated for each language by adding the scores on the two subtests.

During the fMRI experiment, participants were visually presented with a series of single-words on a rear projection video display via a mirror attached to the scanner head coil. Participants were asked to read each word silently and press a button on a hand-held button box when they read each word. A covert reading task was chosen for several reasons as opposed to a lexical decision task or a picture naming task. Bilingual children are learning two different languages and show a somewhat uneven change in language proficiency relative to monolingual children. Previous work in our laboratory (Kohnert, Bates and Hernandez, 1999) has found that Spanish-English bilingual children show improvement in picture naming between the ages of 5 and 14. However, children can show up to 50% error rates in Spanish picture naming despite having much higher accuracy rates when having to match a picture to the correct word for the same lexical items. Gollan et al. (2005) have also shown interference in bilingual adults naming pictures as well. Thus, picture naming was a task that would likely lead to considerable interference in retrieval.

Additionally, lexical decision tasks involve a meta-linguistic component that could cloud the ability to look at language processing in a group of children learning English as a second language during childhood. Lexical decisions in each language become complicated due to the fact that they rely on different lexical and orthographic patterns that might differ across languages. A child who is learning two sets of different patterns may have considerable difficulty with a word-nonword decision, which would appear in their pattern of brain activity. These differences may not be directly related to their language knowledge but to the difficulty in making decisions about language. Thus, a simple word reading task that taps into lexical processing that children could perform competently in both languages was used. The task was covert to reduce movement artifacts in the scanner.

The experimental stimuli consisted of 60 English nouns and 60 Spanish nouns. The number of syllables, AoA, and frequency of the words were controlled across languages. AoA of the stimuli was determined based on unpublished behavioral norms in which monolingual and early bilingual adults estimated the age at which they had learned each word. This method of objectively obtaining AOA has been used in the literature (Morrison, Chappell, and Ellis, 1997). Word frequency was determined using the MCWord orthographic wordform database (Medler & Binder, 2005), which is based on the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995).

The fMRI task utilized a mixed design in which the 60 English nouns and 60 Spanish nouns were presented in four long blocks, 30 words in each block (e.g. 30 English words, 30 English words, 30 Spanish words, 30 Spanish words). The order of blocks was counterbalanced across participants. Within each long block, words were presented in an event-related manner. A computer running Networked Experiment Management Objects software (NEMO; Houston, TX) presented each word on the screen for five seconds, followed by a jittered six to eight second interval, during which time the participant saw a fixation cross. The long block design and 6–8 second ITI was utilized in order to prevent the task from being too cognitively demanding for children. Jittered, irregular interstimulus

intervals were used to prevent expectancy effects in regional cerebral blood flow. All stimuli appeared in white font on a black background. Participants were instructed in English to read the words silently and to press a hand-held button after they had read each word. Immediately following the scan participants were asked to read aloud a list of the same words they saw during the fMRI session in order to measure reading accuracy.

2.3. Imaging Parameters and Analyses

A 3.0 Tesla Siemens Allegra Scanner in the Human Neuroimaging Lab at Baylor College of Medicine was used for the fMRI session. Structural images were obtained during a four and a half minute T_1 -weighted magnetization-prepared radio-frequency pulse and rapid gradient-echo (MP-RAGE) sequence optimized for grey-white matter contrast. One hundred ninety-two whole brain sagittal slices were acquired with a slice thickness of 0.89 mm and an in-plane resolution of 0.96 mm $\times$ 0.96 mm. Functional images were acquired using a T_2^* -weighted echo-planar-imaging (EPI) sequence sensitive to blood-oxygen level dependent (BOLD) signal. Twenty-six transversal slices were acquired in an interleaved, descending manner with a 2000 ms repetition time (TR), 40 ms echo time (TE), a 90-degree flip angle, 4 mm slice thickness, and 3.44 mm $\times$ 3.44 mm in-plane resolution.

Preprocessing and statistical analyses of the fMRI data was performed using Statistical Parametric Mapping 8 (SPM8) software (Wellcome Trust Centre for Neuroimaging, London, UK) running on a Matlab7.8 (The MathWorks, Inc., Natick, MA) platform. Prior to analysis, functional images were corrected for slice timing artifacts, realigned to the T_1 -weighted anatomical scans, co-registered with a canonical brain in MNI space, segmented, normalized, and smoothed with an 8mm full-width half-maximum (FWHM) isotropic Gaussian kernel in order to increase signal-to-noise ratio. The standard MNI template provided by SPM8 was used for the child group as well as the adult group. While rapid growth occurs in infants and very young children, which can result in large variability in brain size, shape, and gray and white matter makeup in these younger age ranges, several seminal studies have shown that the brains of children as young as 7 or 8 can be successfully normalized with adult templates (Burgund et al., 2002; Kang et al., 2003), especially with lower resolution fMRI data. Given the resolution of the smoothed fMRI data, adult templates can be adequate for normalization of fMRI data in the current age range of 8–13 years old ($M = 10.42$, $SD = 1.57$) (Burgund et al., 2002; Kang et al., 2003). According to Evans et al. (2012), errors in analysis become larger when using structural or functional imaging data with much higher resolution. Given the resolution and smoothing of our fMRI data, as well as the higher average age of children in this study, a child specific template was not necessary.

The first four volumes acquired for each participant were removed from analyses so as to allow for stabilization of the BOLD signal. Stimulus presentation onsets were calculated for each condition (i.e. English words, Spanish words, fixation) and modeled against an implicit baseline (mean signal during unmodeled, task-free periods). The first-level involved a fixed effects analysis to create t-contrast images for each condition at the subject level. The condition contrasts for each subject were entered into a second-level random effects analysis to determine cortical regions that were activated both within- and between-groups.

Individual group (i.e. Adults, Children) effects were evaluated using two separate one-way ANOVAs in SPM8 (Wellcome Trust Centre for Neuroimaging, London, UK) with English and Spanish as the within-subjects factors. Within-group whole-brain results were examined at a conservative family wise error (FWE) corrected threshold, $p < .05$. In addition, a conjunction analysis was done to reveal the areas of language cortex that were active across both groups in both English and Spanish. For specific hypotheses involving comparisons in each language across age groups (i.e. Adult English > Child English; Adult Spanish > Child Spanish), an ROI analysis was done using coordinates for six regions obtained from Taylor et al. (2013). Specifically, the ROI analysis involved creating 15 mm spheres surrounding peaks targeted in the right and left MTG ($\pm 50, -66, 18$), IPL ($\pm 36, -48, 46$) and the IFG ($\pm 46, 6, 26$) based on coordinates provided by Taylor et al. (2013). Only peaks with FWE-corrected p values less than or equal to .05 were reported as significant. As noted earlier, since the right hemisphere has been shown to be more active in children, both right and left hemisphere homologues were chosen for each region of interest. Finally, peaks of activation were confirmed through anatomical labeling in Anatomy Toolbox in SPM (Eickhoff et al., 2005). Coordinates are listed in MNI space and figures are displayed using both Anatomy Toolbox and xjview (<http://www.alivelearn.net/xjview>).

3. RESULTS

3.1. Behavioral Results

Behavioral data were analyzed with SPSS version 20.0 (SPSS IBM, Armonk, New York, USA). A one-way MANOVA revealed significant differences between adults and children on behavioral measures, $F(7, 31) = 9.894, p < .0001$; Pillai's Trace = .742, Partial Eta Squared = .742. Follow-up tests revealed that age did not have a statistically significant effect on Spanish picture vocabulary ($F(1, 39) = .023, p = .880$; Partial Eta Squared = .001), composite Spanish proficiency ($F(1, 39) = 2.978, p = .092$; Partial Eta Squared = .071), or the post fMRI Spanish reading accuracy test ($F(1, 39) = 2.173, p = .149$; Partial Eta Squared = .053). However, adults and children did differ on all other metrics (Table 1). In other words, adults had higher scores than children on the English proficiency tests and the Spanish comprehension test, but not on the other Spanish proficiency assessments. Additionally, adults were more accurate than children on the English word reading task given after the fMRI scan; however, adults and children's performance was not significantly different on the Spanish word reading task given after the fMRI scan. Therefore, behavioral differences between adult and child bilinguals were mostly limited to the second language, English.

3.2. Imaging Results

Adults—The first within-subjects ANOVA showed that adults activated a robust, bilateral set of inferior frontal, posterior middle/inferior temporal, subcortical, and cerebellar regions in response to reading English words (Table 2). A similar set of regions was activated when reading in Spanish, again with the left hemisphere inferior frontal region showing the strongest activation (Table 2). In both languages, the most robust region of activation extended from the left inferior frontal gyrus to the subcortical putamen and thalamus. There

were no significant differences between the English and Spanish subtraction contrasts in adults at the conservative FWE corrected threshold, $p < .05$.

Children—An additional within-subjects ANOVA in children showed a different, more subcortically localized pattern of brain activity in response to reading words in English and Spanish. Children showed a more left lateralized network that included the thalamus, caudate, anterior cingulate cortex, and insula when reading English words (Table 2). When reading in Spanish, children activated the left caudate and the right cingulate cortex (Table 2). There were no significant differences in activation between English and Spanish conditions at the conservative FWE corrected threshold, $p < .05$.

Conjunction analysis across languages and groups—In order to evaluate areas recruited by both adults and children in both languages, the contrast of all words (English + Spanish) in adults was inclusively masked by the contrast of all words (English + Spanish) in children. Both groups recruited a large region (left dominant) extending from subcortical regions, including the thalamus, putamen, and caudate, to the insula and inferior frontal cortex (Table 3 and Figure 1). These are regions characteristically recruited in language processing (Taylor et al., 2013).

ROI analysis of the group by language interaction—In line with their behavioral differences in L2 (English) proficiency (Table 1), ROI analyses more specifically determined significant neural differences between adults and children when visually processing words in their L2 (i.e. Adults English > Children English), as seen in Table 4 and Figure 2. Adults recruited bilateral MTG to a greater extent than children.

Comparisons between adults and children in Spanish (i.e. Adults Spanish > Children Spanish) also yielded neural differences despite the fact that there were no behavioral differences in composite Spanish proficiency, Spanish picture vocabulary, or the performance on the post-fMRI Spanish reading task (Table 1). Specifically, there was increased activity in the right MTG in adults relative to children (Table 4 and Figure 2). Given the role of the MTG in semantic processing, and adults increased listening comprehension in Spanish (Table 1), this suggests that when reading words in Spanish, adults rely more heavily on semantic processing.

4. DISCUSSION

The aim of the present study was to compare the neural correlates of reading single words in bilingual children and adults in both their first language and their early-learned second language. This is the first known published fMRI study to directly compare bilingual children and adults in a word reading task in both L1 and L2. Although both children and adults were expected to recruit a network of classic language areas in occipitotemporal, temporoparietal, and frontal cortices, skill and developmental differences were also expected (Booth et al., 2004; Chou et al., 2006; Cone et al., 2008; Gaillard et al., 2003; Holland et al., 2001; Shaywitz et al., 2002; Turkeltaub et al., 2003).

Supporting our predictions, both adults and children recruited a bilateral but left dominant set of regions extending from the subcortical thalamus and basal ganglia to the insula and inferior frontal gyrus (Table 3 and Figure 1). In addition, we observed increased activity in adults relative to children in the MTG, an area that is traditionally thought to be involved in reading (Table 4 and Figure 2). Whereas studies of age-related changes in reading with monolinguals have found differences to be focused in the left hemisphere (Booth et al., 2008; Chou et al., 2006), the current study with bilinguals found a pattern of right lateralized increases in adults relative to children. The results suggest an interesting possible difference in the brain activity that distinguishes adults from children when reading.

One interesting question that emerges from our results is to what extent bilinguals' pattern of right hemisphere differences across age deviates from that seen in monolinguals. Earlier we noted that some studies found more right hemisphere activity in children relative to adults (Booth et al., 2004; Turkeltaub et al., 2002). Moreover, work in the literature has begun to reveal the importance of right hemisphere homologues in language processing (Chiarello & Beeman, 1997; Hartwigsen & Siebner, 2012; Powers et al., 2012). These studies do not contest the fact that the left hemisphere plays a crucial role in language processing. Rather, these studies suggest that the use of right hemisphere homologues during language processing may be much more essential for non-neurologically impaired individuals than previously thought. Thus, reading in bilinguals does not necessarily rely on areas that are not seen at all within the monolingual literature. Rather, the current findings suggest that bilingual adults may be utilizing right hemisphere homologues to a greater extent than bilingual children. In short, they reveal a pattern of adult right hemisphere recruitment that is not typically seen in developmental studies of monolingual reading. We will return to this point later.

The results from the present study also revealed differences in brain activity between adults and children in both L1 and L2 as a function of proficiency, thereby allowing us to look at two slightly different aspects of development. In Spanish, their L1, children and adults showed no overall differences in language proficiency and only minor differences in listening comprehension. This is in line with previous studies of similar bilingual populations that find a much smaller rate of improvement in the first language after the age of 7 (Kohnert et al., 1999). In English, their L2, on the other hand, adults showed significant improvements over children in language proficiency (Table 1). Comparisons across age groups revealed increased activity in adults in the bilateral MTG when reading English words. In Spanish, their L1, only the right MTG survived the corrected threshold. These imaging results are consistent with the behavioral results. Specifically, the greatest neural differences across age groups were observed in English, the language that had the largest skill differential. In Spanish, where there were minimal age-related differences in proficiency, a similarly small difference was observed in brain activity. Hence, these results suggest that activity in the right MTG may show age-related differences even when there is much less of a difference in language-skill development. Future studies are needed to further investigate the relationship between proficiency changes and age changes in children and adults.

The increased activity observed in MTG across both languages and in each language separately when comparing adults to children suggests that it plays a crucial role in reading. Previous studies have consistently reported activation of left MTG for tasks requiring access to semantic representations (Binder et al., 2009; Pugh et al., 2005; Taylor et al., 2012), as well as increases in MTG for lexical processing as a function of skill and development (Cohen et al., 2008). This suggests that when visually processing words in either language, adults automatically accessed word meaning in order to facilitate word recognition, a more advanced skill. The fact that this difference appeared in both hemispheres in English suggests that semantic processing is of crucial importance in reading words for bilinguals. The fact that activity in the MTG only appears in the right hemisphere for Spanish is particularly intriguing since there was little change in skill in overall Spanish proficiency. This finding is not consistent with previous findings of greater right hemisphere involvement in childhood (Booth et al., 2004; Turkeltaub et al., 2002) and suggests that recruitment of left hemisphere regions is not likely to occur when skill development in that language is diminished. One possibility is that language and reading skill may dissociate in individuals who read two languages. Studies of laterality have found that activity in right posterior portions of the brain involved in reading are correlated with reading ability (Van Ettinger-Veenstra, Ragnehed, McAllister, Lundberg, & Engstrom, 2012; Van Ettinger-Veenstra et al., 2010). A second possible interpretation of our findings is that bilingual adults improved skill in reading in both languages may be leading to increased activity in the right hemisphere in Spanish and English. Future studies are needed to further evaluate this possibility.

5. LIMITATIONS

The presence of right hemisphere areas that distinguish adult from child brain activity while reading words does not imply that there is no activity in the left hemisphere language areas. Indeed, wide areas of brain activity were observed in the conjunction analysis of adult and child brain activity. The use of a conservative threshold and small groups could lead one to conclude that neither of the two groups used traditional left areas of the brain when processing words. However, this is the product of using very conservative thresholds in the current study in some cases. Future studies could overcome this limitation by using an uncorrected threshold, using robust statistics that are more sensitive to subtle changes in smaller groups of participants, or by increasing the size of the groups tested. Finally, future studies could use a regression approach, including both proficiency and age across a group that varies to a greater extent in this respect. Future studies that use these approaches are needed in order to investigate whether the use of conservative thresholds with small groups of participants may not be indicative of the range of differences that could potentially be observed across adult and child bilinguals. The use of regression approaches might also help in this respect.

The presence of right hemisphere activity could also indicate that adults may engage in higher-level language processing. Some studies suggest that right hemisphere brain activity may be present when looking at the processing of metaphors (Benedek et. al, 2014). However, closer review of this study shows considerable left hemisphere activity. Furthermore, a recent review of the literature (Ferstl et. al, 2008) shows a very similar result to that observed in the current study. There was considerable left hemisphere activity and

some right hemisphere activity during language processing. The presence of right hemisphere differences between adults and children is particularly interesting. The possibility that adults may engage in higher-level language processing could be a tenable hypothesis. However, it is beyond the scope of the current study and requires more work with bilingual participants using a variety of different types of language stimuli.

6. CONCLUSION

The present study compared the neural correlates of lexical processing in bilingual children and adults using a single-word reading task and was the first known fMRI study to directly compare bilingual children and adults. Results revealed a broad network of classic language areas similarly recruited by both children and adults when visually processing words in both their languages, as well as crucial differences between children and adults. Increased activity in the bilateral MTG was observed between adults and children in English, the language that showed the largest changes in proficiency. In Spanish, the language that showed very minimal changes in proficiency, only the right MTG revealed differential activation across age groups. Taken together, these results highlight the importance of right homologues in reading in bilingual adults relative to children. These results extend those seen in the monolingual literature by revealing the influence of proficiency and bilingualism on the brain areas that often differentiate adults from children during reading of single words.

Acknowledgments

Support for this research was provided by the Institute for Biomedical Imaging Science (IBIS) grant “Plasticity In Speech Perception In Early Bilingual Children”, and NIH/NICHD grant “Neural correlates of lexical processing in child L2 learners” (R21HD059103-01).

References

- Archila-Suerte P, Zevin J, Ramos A, Hernandez A. The Neural Basis of Non-Native Speech Perception in Bilingual Children. *NeuroImage*. 2012; 67(15):51–63. [PubMed: 23123633]
- Baayen, RH., Piepenbrock, R., Gulikers, L. The CELEX lexical database (Release 2) [CD-ROM]. Philadelphia, PA: Linguistic Data Consortium, University of Pennsylvania [Distributor]; 1995.
- Benedek M, et al. Creating metaphors: The neural basis of figurative language production. *NeuroImage*. 2014; 90:99–106. [PubMed: 24384149]
- Binder JR, Desai RH, Graves WW, Conant LL. Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*. 2009; 19(2):2767–2796. [PubMed: 19329570]
- Bitan T, Burman DD, Chou TL, Lu D, Cone NE, Cao F, Bigio JD, Booth JR. The interaction between orthographic and phonological information in children: an fMRI study. *Human Brain Mapping*. 2007; 28:880–891. [PubMed: 17133384]
- Bolger DJ, Hornickel J, Cone NE, Burman DD, Booth JR. Neural correlates of orthographic and phonological consistency effects in children. *Human Brain Mapping*. 2008; 29:1416–1429. [PubMed: 17957704]
- Booth, JR. Brain bases of learning and development of language and reading. In: Coch, D., editor. *Human Behavior, Learning, and the Developing Brain*. New York: Guilford Press; 2007. p. 279–300.
- Booth JR, Burman DD, Meyer JR, Zhang L, Gitelman DR, Parrish TR, Mesulam MM. Development of brain mechanisms for processing orthographic and phonological representations. *Journal of Cognitive Neuroscience*. 2004; 16:1234–1249. [PubMed: 15453976]

- Booth JR, Lu D, Burman DD, Chou TL, Jin Z, Peng DL, Zhang L, Ding GS, Deng Y, Liu L. Specialization of phonological and semantic processing in Chinese word reading. *Cognitive Brain Research*. 2006; 1071:197–207.
- Booth JR, Mehdiratta N, Burman DD, Bitan T. Developmental increases in effective connectivity to brain regions involved in phonological processing during tasks with orthographic demands. *Brain Research*. 2008; 1189:78–89. [PubMed: 18068690]
- Burgund ED, Kang HC, Kelly JE, Buckner RL, Snyder AZ, Petersen SE, Schlaggar BL. The feasibility of a common stereotactic space for children and adults in fMRI studies of development. *NeuroImage*. 2002; 17:184–200. [PubMed: 12482076]
- Chee MWL, Tan EWL, Thiel T. Mandarin and English single word processing studied with functional magnetic resonance imaging. *Journal of Neuroscience*. 1999; 19:3050–3056. [PubMed: 10191322]
- Chiarello C, Beeman M. Toward a veridical interpretation of right-hemisphere processing and storage. *Psychological Science*. 1997; 8(4):343–344. DOI: 10.1111/j.1467-9280.1997.tb00451.x
- Chou TL, Booth JR, Bitan T, Burman DD, Bigio JD, Cone NE, Lu D, Cao F. Developmental and skill effects on the neural correlates of semantic processing to visually presented words. *Human Brain Mapping*. 2006; 27:915–924. [PubMed: 16575838]
- Cohen L, Dehaene S, Vinckier F, Jobert A, Montavont A. Reading normal and degraded words: Contribution of the dorsal and ventral visual pathways. *NeuroImage*. 2008; 40:353–366. [PubMed: 18182174]
- Cone NE, Burman DD, Bitan T, Booth JR. Developmental changes in brain regions involved in phonological and orthographic processing in spoken language processing. *NeuroImage*. 2008; 41:623–635.
- Das T, Padakannaya P, Pugh KR, Singh NC. Neuroimaging reveals dual routes to reading in simultaneous proficient readers of two orthographies. *NeuroImage*. 2011; 54:1476–1487. [PubMed: 20854914]
- Eickhoff S, Stephan KE, Mohlberg H, Grefkes C, Fink GR, Amunts K, Zilles K. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. *NeuroImage*. 2005; 25:1325–1335. [PubMed: 15850749]
- Evans AC, Janke AL, Collins DL, Baillet S. Brain templates and atlases. *NeuroImage*. 2012; 62:911–922. [PubMed: 22248580]
- Ferstl EC, Neumann J, Bogler C, von Cramon DY. The extended language network: a meta-analysis of neuroimaging studies on text comprehension. *Human Brain Mapping*. 2008; 29:581–593. [PubMed: 17557297]
- Gaillard WD, Sachs BC, Whitnah JR, Ahmad Z, Balsamo LM, Petrella JR, Branietcki SH, McKinney CM, Hunter K, Xu B, Grandin CB. Developmental aspects of language processing: fMRI of verbal fluency in children and adults. *Human Brain Mapping*. 2003; 18:176–185. [PubMed: 12599275]
- Gollan TH, Montoya RI, Fennema-Notestine C, Morris SK. Bilingualism affects picture naming but not picture classification. *Memory & Cognition*. 2005; 33:1220–1234. [PubMed: 16532855]
- Hartwigsen G, Siebner HR. Probing the involvement of the right hemisphere in language processing with online transcranial magnetic stimulation in healthy volunteers. *Aphasiology*. 2012; 26(9): 1131–1152. DOI: 10.1080/02687038.2011.590573
- Hernandez AE, Li P. Age of acquisition: Its neural and computational mechanisms. *Psychological Bulletin*. 2007; 133(4):638–650. [PubMed: 17592959]
- Holland SK, Plante E, Byars AW, Strawsburg RH, Schmithorst VJ, Ball WS Jr. Normal fMRI Brain Activation Patterns in Children Performing a Verb Generation Task. *NeuroImage*. 2001; 14:837–843. [PubMed: 11554802]
- Jamal NI, Piche AW, Napoliello EM, Perfetti CA, Eden GF. Neural basis of single-word reading in Spanish-English bilinguals. *Human Brain Mapping*. 2012; 33:235–245. [PubMed: 21391265]
- Johnson MH. Interactive Specialization: A domain-general framework for human functional brain development? *Developmental Cognitive Neuroscience*. 2011; 1:7–21. [PubMed: 22436416]
- Kang HC, Burgund D, Lugar HM, Petersen SE, Schlaggar BL. Comparison of functional activation foci in children and adults using a common stereotactic space. *NeuroImage*. 2003; 19:16–28. [PubMed: 12781724]

- Kohnert KJ, Bates E, Hernandez AE. Balancing bilinguals: Lexical-semantic production and cognitive processing in children learning Spanish and English. *Journal of Speech, Language, and Hearing Research*. 1999; 42:1400–1413.
- Medler, DA., Binder, JR. MCWord: An on-line orthographic database of the English language. 2005. <http://www.neuro.mcw.edu/mcword/>
- Meschyan G, Hernandez AE. Impact of language proficiency and orthographic transparency on bilingual word reading: An fMRI investigation. *Neuroimage*. 2006; 29:1135–1140. [PubMed: 16242351]
- Morrison CM, Chappell TD, Ellis AW. Age of acquisition norms for a large set of object names and their relation to adult estimates and other variables. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*. 1997; 50A:528–559.
- Nakamura J, Kouider S, Makuuchi M, Kuroki C, Hanajima R, Ugawa Y, Ogawa S. Neural control of cross-language asymmetry in the Bilingual Brain. *Cerebral Cortex*. 2010; 20:2244–2251. [PubMed: 20051357]
- Perani D, Abutalebi J. The neural basis of first and second language processing. *Current Opinions in Neurobiology*. 2005; 15:202–206.
- Powers C, Bencic R, Horton WS, Beeman M. Hemispheric inference priming during comprehension of conversations and narratives. *Neuropsychologia*. 2012; 50(11):2577–2583. DOI: 10.1016/j.neuropsychologia.2012.07.008 [PubMed: 22820639]
- Price CJ. The anatomy of language: Contributions from functional neuroimaging. *Journal of Anatomy*. 2000; 197:335–359. [PubMed: 11117622]
- Pugh KR, Mencl WE, Shaywitz BA, Shaywitz SE, Fulbright RK, Constable RT, Skudlarski P, Marchione KE, Jenner AR, Fletcher JM, Liberman AM, Shankweiler DP, Katz L, Lacadie C, Gore JC. The angular gyrus in developmental dyslexia: Task-specific differences in functional connectivity within posterior cortex. *Psychological Science*. 2000; 11:51–56. [PubMed: 11228843]
- Pugh KR, Sandak R, Frost SJ, Moore D, Cencel E. Examining reading development and reading disability in English language learners: Potential contributions from functional neuroimaging. *Learning Disabilities Research & Practice*. 2005; 20(1):24–30.
- Shaywitz BA, Shaywitz SE, Pugh KR, Mencl WE, Fulbright RK, Skudlarski P, Constable RT, Marchione KE, Fletcher JM, Lyon GR, Gore JC. Disruption of posterior brain systems for reading in children with developmental dyslexia. *Society of Biological Society*. 2002; 52:101–110.
- Taylor JS, Rastle K, Davis MH. Can cognitive models explain brain activation during word and pseudoword reading? A meta-analysis of 36 neuroimaging studies. [Research Support, Non-U.S. Gov't]. *Psychol Bull*. 2013; 139(4):766–791. DOI: 10.1037/a0030266 [PubMed: 23046391]
- Tatsuno Y, Sakai K. Language-related activations in the left prefrontal regions are differentially modulated by age, proficiency, and task demands. *Journal of Neuroscience*. 2005; 25(7):1637–1644. [PubMed: 15716399]
- Tan LH, Chen L, Yip V, Chan AHD, Yang J, Gao J-H, et al. Activity levels in the left hemisphere caudate-fusiform circuit predict how well a second language will be learned. *Proceedings of the National Academy of Sciences USA*. 2011; 108:2540–2544.
- Turkeltaub P, Eden G, Jones K, Zeffiro T. Meta-analysis of the functional neuroanatomy of single-word reading: Method and validation. *Neuroimage*. 2002; 16:765–780. [PubMed: 12169260]
- Van Ettinger-Veenstra HM, Ragnehed M, McAllister A, Lundberg P, Engstrom M. Right-hemispheric cortical contributions to language ability in healthy adults. *Brain Lang*. 2012; 120(3):395–400. [PubMed: 22115846]
- Van Ettinger-Veenstra HM, Ragnehed M, Hallgren M, Karlsson T, Landtblom AM, Lundberg P, Engstrom M. Right-hemispheric brain activation correlates to language performance. *Neuroimage*. 2010; 49(4):3481–3488. [PubMed: 19853040]
- Woodcock, RW. Woodcock Language Proficiency Battery-Revised. Riverside Publishing; Itasca, IL: 1991.
- Xue G, Dong Q, Jin Z, Zhang L, Wang Y. An fMRI study with semantic access in low proficiency second language learners. *Neuroreport*. 2004; 15(5):791–796. [PubMed: 15073516]

Appendix. English and Spanish Stimuli

English					
Stimulus	Condition	Frequency	Syllables	AOA	Concreteness
building	HIGH	160.33	2	4.51	589
day	HIGH	772.04	1	3.76	477
garden	HIGH	114.11	2	4.54	602
hand	HIGH	470.11	1	2.97	604
money	HIGH	386.52	2	4.19	574
morning	HIGH	305.26	2	4.00	515
mother	HIGH	446.20	2	2.76	579
number	HIGH	302.28	2	3.59	395
party	HIGH	373.50	2	4.65	496
picture	HIGH	102.21	2	3.70	579
population	HIGH	108.10	4	7.95	406
room	HIGH	476.00	1	3.89	566
teacher	HIGH	71.75	2	4.24	569
village	HIGH	140.05	2	6.24	576
window	HIGH	137.96	2	3.59	609
aircraft	LOW	45.45	2	6.41	603
angle	LOW	21.60	2	7.38	467
bureau	LOW	16.60	2	9.81	547
cattle	LOW	33.20	2	5.41	600
copper	LOW	17.91	2	7.30	547
essay	LOW	13.39	2	8.49	527
feather	LOW	5.83	2	4.73	622
friendship	LOW	25.05	2	4.84	335
hunger	LOW	25.22	2	4.03	410
mayor	LOW	15.53	2	8.51	507
mill	LOW	10.65	1	7.35	584
network	LOW	24.15	2	9.24	429
profile	LOW	10.89	2	9.24	510
shadow	LOW	37.48	2	4.51	457
witness	LOW	23.74	2	8.14	459
<i>M</i>		156.44	1.93	5.67	524.67
<i>SD</i>		194.35	0.52	2.12	76.36

Note-Frequency is from the MCWord Orthographic Wordform Database (Medler, D. A. & Binder, J. R., 2005); AOA is age of acquisition, objectively determined; Concreteness is from the MRC Psycholinguistic Database (Wilson, 1988)

Spanish						
Stimulus	Translation	Condition	Frequency	Syllables	AOA	Concreteness
ciudad	city	HIGH	220.66	2	5.38	554

Spanish						
Stimulus	Translation	Condition	Frequency	Syllables	AOA	Concreteness
cuenta	count	HIGH	80.79	2	6.43	351
puerta	door	HIGH	343.87	2	3.52	606
cara	face	HIGH	467.02	2	3.21	599
frente	front	HIGH	263.08	2	3.97	424
oro	gold	HIGH	91.62	2	5.53	576
rey	king	HIGH	91.74	1	4.35	559
ley	law	HIGH	152.30	1	7.47	349
carta	letter	HIGH	121.43	2	5.78	577
amor	love	HIGH	364.16	2	3.71	311
lector	reader	HIGH	31.59	2	7.85	483
rio	river	HIGH	113.57	2	4.32	585
sol	sun	HIGH	155.22	1	3.30	617
viaje	trip	HIGH	59.49	2	5.23	448
voz	voice	HIGH	241.90	1	4.12	485
cerca	fence	LOW	23.20	2	4.87	597
carbon	coal	LOW	37.84	2	6.41	584
polvo	dust	LOW	47.59	2	5.47	550
motor	engine	LOW	43.79	2	5.95	586
prenda	garment	LOW	10.53	2	6.64	552
hierba	herb	LOW	10.23	2	5.38	558
lago	lake	LOW	42.48	2	5.87	585
nivel	level	LOW	186.03	2	6.56	422
barro	mud	LOW	30.64	2	7.25	605
nariz	nose	LOW	75.32	2	3.18	628
arroz	rice	LOW	27.49	2	3.32	608
cuerda	rope	LOW	33.49	2	6.21	608
tiro	shot	LOW	89.72	2	5.65	467
tallo	stem	LOW	11.66	2	6.86	556
trato	treatment	LOW	68.00	2	6.52	343
<i>M</i>			117.88	1.87	5.34	525.77
<i>SD</i>			116.76	0.35	1.37	93.81

Note-Frequency is from the MCWord Orthographic Wordform Database (Medler, D. A. & Binder, J. R., 2005); AOA is age of acquisition, objectively determined; Concreteness is from the MRC Psycholinguistic Database (Wilson, 1988)

Figure 1.
Conjunction Analysis: Common Regions of Activation Between Adults and Children.

Figure 2. ROI Analysis

A) Adult English > Child English: left and right MTG; B) Adult Spanish > Child Spanish: right MTG

Table 1

Demographic and Behavioral Data

	Adults (n = 20)	Children (n = 21)	F	p
Age [mean (SD)]	21.55 (2.14)	10.52 (1.57)	356.65	< .0001 *
AOA [mean (SD)]	3.95 (2.17)	3.67 (1.20)	0.262	.6120
% of Day in English [mean (SD)]	73.50 (15.40)	54.76 (18.34)	12.49	.001 *
% of Day in Spanish [mean (SD)]	28.25 (15.41)	45.24 (18.33)	10.26	.003 *
Manova:				
WLPB-PVE [mean (SD)]	37.55 (4.16)	29.74 (2.95)	43.52	< .0001 *
WLPB-PVS [mean (SD)]	29.85 (3.76)	29.68 (3.24)	0.02	.880
WLPB-LCE [mean (SD)]	29.85 (3.01)	21.95 (3.09)	68.64	< .0001 *
WLPB-LCS [mean (SD)]	28.10 (3.68)	25.11 (2.68)	8.92	.005 *
Composite E [mean (SD)]	67.40 (5.87)	51.68 (5.43)	79.27	< .0001 *
Composite S [mean (SD)]	57.95 (6.60)	54.79 (5.07)	2.98	.092
Post-Scan Accuracy E % [mean (SD)]	99.50 (0.21)	95.41 (0.76)	25.56	< .0001 *
Post-Scan Accuracy S % [mean (SD)]	99.00 (0.31)	97.84 (0.71)	2.17	.149
Scanner Task E RT [mean (SD)]	1277.97 (160.67)	2302.33 (237.41)	12.52	.001 *
Scanner Task S RT [mean (SD)]	1314.41 (169.68)	2290.14 (245.88)	10.47	.002 *

Note:

* designates significance, $p < .05$;

AOA = Age of Acquisition; WLPB = Woodcock Language Proficiency Battery (Woodcock, 1991); PVE = Picture Vocabulary in English; PVS = Picture Vocabulary in Spanish; LCE = Listening Comprehension in English; LCS = Listening Comprehension in Spanish; E = English; S = Spanish; RT = Reaction Time.

Table 2

Within-Subjects ANOVAs for Adults and Children

Adults								
<i>p</i>	Contrast	Area	Hemisphere	Voxels (k)	x	y	z	Z
FWE < .05	English	Inferior frontal gyrus extends to putamen & thalamus	L	2093	-42	10	0	6.48
		Inferior frontal gyrus and insula	R	279	40	10	2	5.44
		Posterior middle/inferior temporal junction	L	148	-42	-62	-8	5.33
		Putamen and thalamus	R	117	24	-8	12	4.82
		Posterior middle/inferior temporal junction	R	77	42	-54	-14	5.36
FWE < .05	Spanish	Cerebellum lobule V	R	47	16	-46	-18	4.99
		Inferior frontal gyrus extends to putamen & thalamus	L	1541	-46	8	6	6.1
		Posterior middle/inferior temporal junction	L	262	-46	-60	-6	5.91
		Inferior frontal gyrus	R	168	40	10	0	5.3
		Posterior middle/inferior temporal junction	R	102	42	-54	-14	5.41
FWE < .05	E > S	None at threshold						
FWE < .05	S > E	None at threshold						
Children								
<i>p</i>	Contrast	Area	Hemisphere	Voxels (k)	x	y	z	Z
FWE < .05	English	Thalamus	L	27	-2	-16	12	4.85
		Caudate	L	13	-14	-10	18	4.59
		Anterior cingulate	L	9	-2	20	30	4.42
		Insula	L	8	-36	10	6	4.39
		Caudate	L	34	-16	-8	18	4.78
FWE < .05	Spanish	Posterior cingulate	R	28	2	-24	28	4.54
FWE < .05	E > S	None at threshold						
FWE < .05	S > E	None at threshold						

Note: Coordinates are in MNI space; E=English; S=Spanish; FWE=Family Wise Error corrected threshold, $p < .05$.

Table 3

Conjunction Analysis Across Adults and Children

<i>p</i>	Contrast	Area	Hemisphere	Voxels (k)	x	y	z	Z
FWE <.05	English + Spanish *	IFG/Insula/Subcortical regions	Bilateral	4364	-42	10	0	7.5
		Insula lobe	L		-42	10	0	
		Insula lobe	R		42	10	0	
		Putamen	L		-26	-14	2	
		Thalamus	L		-14	-2	10	
		Putamen	L		-28	-10	2	
		Caudate	L		-16	-4	14	
		Middle cingulate cortex	L	675	-2	14	36	5.7
		Postcentral gyrus	L	97	-52	-20	22	4.25

Note: Coordinates are in MNI space; AE=Adult English, AS=Adult Spanish, CE=Child English, CS=Child Spanish;

* designates (AE + CE) masked inclusively by (AS + CS)

Table 4

ROI Analysis

Condition	Search Volume	Peak-level <i>p</i> , FWE corrected	Hemisphere	Voxels (k)	Area	x	y	z	Z
AS > CS	15	0.001	R	123	MTG	38	-68	18	4.36
AE > CE	15	0.006	L	159	MTG	-42	-56	12	3.97
	15	0.004	R	129	MTG	40	-66	18	4.09

Note: Coordinates are in MNI space; AE=Adult English, AS=Adult Spanish, CE=Child English, CS=Child Spani