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NEURAL NETWORKS UNDERLYING LANGUAGE PROCESSING IN SAME SCRIPT BILINGUALS: AN INVESTIGATION OF FUNCTIONAL SPECIFICITY IN

THE VISUAL WORD FORM AREA

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ABSTRACT OF THE DISSERTATION

Neural Networks Underlying Language Processing in Same Script Bilinguals: An Investigation of the Functional Specificity in the Visual Word Form Area.

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A small area in the inferior occipito-temporal cortex of the brain named the Visual Word Form Area (VWFA) was shown to be involved in recognition of written words. This area becomes more active when participants view written words as compared to other kinds of visual stimuli, such as checkerboard patterns (e.g., Cohen et al., 2000; 2002), digits (Polk et al., 2002), or geometric shapes (Gros et al., 2001). This dissertation research examined how functional specialization to written words emerges in the VWFA as a function of language experience and how the response in this area may rapidly adapt to the constraints imposed by the characteristics of the visual input. VWFA activity was measured with fMRI in two samples of same-script bilingual speakers, who varied in the level of proficiency across two languages. In Experiments 1 and 2, activity for first and second language words was contrasted with checkerboard pattern baseline. Both overlapping and distinct areas of activation within VWFA were found for each language. The extent of activation overlap for first and second language was related to participants' language proficiency and age of acquisition. This result was confirmed by univariate (Experiment 1) and multivariate (Experiment 2) analyses. In Experiment 3, repetition suppression was observed in the VWFA for word-pairs with similar orthography (homographs), but not for word-pairs with similar orthography and meaning (cognates), indicating that the VWFA is sensitive to semantic information. In addition, graphical connectivity analyses revealed that the more proficient language activated a ventral route from the VWFA to the prefrontal areas, and the less proficient language activated a dorsal route. Experiment 4 tested whether neural activity in the VWFA increases when target words are semantically congruent with the rest of the words in a sentence. The results showed that while the VWFA activity is buffered against repetition suppression by semantic similarity between single words, the VWFA is not sensitive to sentence level congruency. Collectively, the results suggest that the VWFA supports abstract orthographic processing, with similar mechanisms employed for early-acquired samescript languages, and that it participates in the integration of incoming visual information with single word semantics.

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Chapter 1: General Introduction

Overview

Visual word recognition is a fundamental human capacity, which helps to encode and transmit the wealth of human knowledge. This capacity developed fairly recently in the evolutionary history owing to the advent of written language. Visual word recognition has been identified with activation in a small brain area in the inferior occipito-temporal cortex called the Visual Word Form Area (VWFA; first investigated by Déjerine, 1892 as cited in Cohen et al., 2000). The VWFA is located in the middle to posterior part of the fusiform gyrus (centered on Talairach coordinates x = -44, y = -58, z = -15; Jobard et al., 2003), and has been shown to preferentially respond to visual forms of written words (e.g., Cohen et al., 2000; 2002). However, the exact nature of neural processing in the VWFA is currently under debate. Some claim that this area becomes functionally specialized for processing visual word-forms as people acquire reading skills (e.g., Vinckier et al., 2007; Glezer et al., 2009), while others suggest that the VWFA also responds to pictures and may help to integrate word-forms with their meaning (e.g., Price & Devlin, 2003, 2004; Devlin et al., 2006). Much of this work has assessed monolingual activation of VWFA. However, a new direction of research with bilingual speakers (e.g., Perfetti et al., 2007; Nelson et al., 2009) may provide greater insight into neural processing in the VWFA by quantifying its response to lexical items belonging to different languages and by assessing its sensitivity to overlap of visual form and meaning across two languages. For example, when Spanish-English bilinguals read a pair of items

like the English word *carpet* and the Spanish word *carpeta* [folder] their VWFA may respond (1) to the visual similarity between these words, (2) to the semantic dissimilarity between them, or (3) may store information about the language membership of each word. These different outcomes can speak to the degree of this area's functional specialization for processing word forms, if any, and may help to determine how its activity is modified by experience with a second language. Furthermore, in speakers of multiple languages it becomes possible to independently manipulate single word consistency across languages (e.g., by using words like *carpet - carpeta*), as well as sentence-level congruency (e.g., *The baker cut the pie/The baker cut the truck*) in order to measure the influences of both bottom up/input-driven and top down/expectancy-driven modulation of this area during reading.

Functional Specialization of the VWFA: Evidence for and against

Previous neuroimaging evidence from Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) studies showed that the VWFA responded more to letters, than to digits (e.g., Polk et al., 2002), or geometric shapes (Gros et al., 2001); and that its response was greater to real words and readable nonwords (e.g., *lebble*) than to consonant strings (e.g., Vinckier et al., 2007), suggesting that this area was sensitive to orthographic regularity. In addition, activity for words in the VWFA was found to be independent of typographic case, supporting its role in storing abstract orthographic representations (e.g., Dehaene et al., 2001; 2004; but see Burgund, Guo, & Aurbach, 2009).

However, not everyone agrees that the VWFA is functionally specialized for reading. Although many studies imply that its activity is important during reading, a

large body of evidence suggests that it does not selectively respond to word forms. Price and Devlin (2003) claimed that the VWFA is a multimodal processing area that cares about object and word identity. Consistently with this idea, several recent functional imaging studies showed that the VWFA responded to a host of stimuli other than visually presented words: the VWFA was activated when participants viewed and named pictures of familiar objects, made manipulation responses to pictures of objects and non-objects, named colors and performed auditory and tactile word processing tasks (see Price & Devlin, 2003 for review). Similarly, Wright and colleagues (2008) found greater activity for pictures relative to words in this area (but see Szwed et al., 2011), and Chao, Weisberg and Martin (2002) found that VWFA responded to pictures of familiar objects and that its activity was influenced by specific category of objects. In addition, Mei et al. (2010) found that stronger activity in the VWFA was associated with better recognition memory of both words and faces. These findings suggested that neural activity in the VWFA may be driven by processes common to object, face, and word-form recognition.

The differences in the outcomes of studies investigating the function of the VWFA imply one of several possibilities. Let us consider these alternatives. The first is that this area is a part of the higher-order visual cortex that processes the kinds of feature conjunctions that are important for discriminating alphabetic and, possibly, non-alphabetic visual stimuli. For example, this area may respond to basic visual elements, such as vertex points at the intersection of lines. Vertices make up many Roman letters and are utilized by the majority of the world's writing systems (Changizi, Zhang, Ye, & Shimojo, 2006; Szwed et al., 2011). Vertices are also important for visual recognition of objects (Biederman, 1987; see Figure 1.1. for illustration). However, while vertex

detection can explain the VWFA response to letters and syllables, it cannot account for its greater response to real words, than to readable non-words (e.g., Glezer et al., 2009) because the distribution of vertices in these stimuli is roughly equivalent. Recently, Szwed and colleagues (2011) also showed that when picture complexity is reduced to the level of line segments and vertices neural activity in the VWFA to such pictures is lower than to words. These, and other similar findings, pose a challenge for an account of the VWFA response, which employs basic visual processing mechanisms.



Figure 1.1: The importance of vertices to visual object recognition.

In the following set of examples about 1/3 of the total image has been deleted. In column A line segments were removed, while preserving the vertices. In column B vertices have been deleted, making it difficult to recognize the visual components and to identify the objects. Slower recognition of items such as those in column B was first demonstrated by Biederman (1987).

A second possibility is that although this area may be somewhat sensitive to various visual stimuli, it is functionally specialized for processing written word forms. The activity in the VWFA becomes increasingly tuned to its preferred stimulus class as a result of accumulating visual experience with print coupled with this area's initial biological predisposition towards responding to features or feature conjunctions that are important for discriminating alphabetic stimuli. Through continued exposure to orthography of a particular writing system the brain may develop and fine-tune the most efficient processing mechanisms that are relevant for the task of reading (e.g., Schlaggar & McCandliss, 2007; McCandliss, Cohen, & Dehaene, 2003; Vinckier et al., 2007). This possibility may be referred to as the functional specialization account of neural processing in the VWFA.

Finally, a third possibility stems from recent neuroimaging findings, which show that neural activity in this area may be modulated by word meaning (e.g., Devlin et al., 2006) and that the VWFA activation during reading is correlated with the activation of left-lateralized areas traditionally associated with semantic processing (e.g., Vigneau, Jobard, Mazoyer, & Tzourio-Mazoyer, 2005). Moreover there is now evidence from studies using Event Related Potentials (ERPs), which shows early impact of semantics on reading (e.g., Penolazzi, Hauk, & Pulvermuller, 2007). These findings indicate that the process of decoding semantic information from lexical items begins as soon as activation reaches the extrastriate areas, such as the VWFA. This possibility implies that the role of the VWFA may extend beyond recognition of orthographic form. This area may serve potentially as an integration region where incoming visual information is coupled with stored lexico-semantics and conveyed to other brain areas in the language network. This possibility views the VWFA as a gateway into the language system, which may process meaning in both linguistic and non-linguistic contexts. This kind of flexibility would explain the VWFA's response to words and other visual stimuli.

The Development of Reading Expertise

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The idea that experience in reading can shape brain function is at the core of the functional specialization account. It is supported by developmental evidence, which shows that when children learn to read, neural activity in the occipito-temporal areas, implicated in reading, changes. During early experience with reading this activity is bilateral, and in the later years it becomes predominantly left-lateralized (e.g., Shaywitz, et al., 2002; Schlaggar et al., 2002). An ERP study showed that modulation of N1 component by visually presented words increased in children after 1.5 years of formal schooling (Maurer et al., 2006). The N1 component of the ERP response is a negative deflection from baseline, often linked to the activity in the VWFA (e.g., Maurer et al., 2005). In addition, insufficient or atypical activity of the VWFA was found in children with reading disabilities (Shaywitz et al., 2002, 2004; Simos et al., 2002) and, more specifically, with dyslexia (Helenius et al., 1999; Paulesu et al., 2001; Salmelin et al., 1996; Simos et al., 2000). Furthermore, slight fine-tuning of the reading system was evident even during adolescence (e.g., Brem et al., 2006). These findings point to the increased tuning of the VWFA response to the emerging reading expertise. However, one caveat of these findings is that they are confounded with maturation of the brain. As many areas of the child's and adolescent's brain are maturing at the same time, changes elsewhere in the brain, for example, in the prefrontal cortex, may drive this pattern of responding (see Price and Devlin, 2004 for more details). Thus, increased VWFA activity may indicate a general shift in neural processing as children transition into adulthood, rather than a development of a specific cognitive function.

A more compelling direction for research will seek to study adult populations in the hopes of disambiguating maturational shifts from the effects of reading ability. Early attempts in that direction have been made. For example, Dehaene et al. (2010) showed an increased response in the VWFA to sentences and letter strings relative to rest in adult participants (Brazilian and Portuguese nationals), who acquired literacy late in life, when these participants were compared to a matched group of adult illiterate participants (Brazilian nationals). The increase in the VWFA activity was significant for the Brazilian ex-literates relative to Brazilian illiterates, but not significant for the Portuguese exliterates relative to the Brazilian illiterates. These results indicate a moderate relationship between literacy and the activity in the VWFA in the absence of maturational changes.

Another participant population, which lends itself easily to this kind of investigation, consists of speakers, who are literate in two languages, or bilinguals. The bilingual word-form recognition system must adapt to unique circumstances owing to the fact that bilinguals must store approximately two word-form representations for every concept, as well as the language membership of each word-form. Such language tagging is essential for producing the correct mapping between orthography, phonology and semantics. Whether language segregation occurs in the VWFA, or elsewhere in the language system has not yet been clearly demonstrated. The answer to this question is important because it speaks to the core of our current understanding of information processing in the VWFA. It can help to gauge the degree of functional flexibility in this region.

Studies that examined speakers of languages with distinct writing systems suggest that the VWFA response is not homogeneous across such languages. Correlates of the reading system in the left and right hemispheres of the brain may be differentially sensitive to first and second language orthographies. For example, Perfetti and

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colleagues (2007) examined the activity of the word-reading system in native English speakers, who were learning Chinese. For these participants, reading in English was associated with activity in the left fusiform gyrus, while reading in Chinese was associated with activity in the bilateral fusiform gyrus. In fluent Chinese-English bilinguals, bilateral fusiform gyrus was activated for both English and Chinese stimuli (Nelson, Liu, Fiez & Perfetti, 2009). These results demonstrated greater reliance of the Chinese writing system on the right homologue of the VWFA, regardless of proficiency, as well as recruitment of the right hemisphere for English, when English was participants' second language. Therefore, evidence from second-language learners indicates that additional brain areas, such as the right VWFA homologue, may be necessary for reading in two visually-distinct writing systems (but see Chee, Caplan, et al., 1999). However, exposure to languages as distinct as English and Chinese may evoke extreme cortical behavior leading to bilateral activation of the mid-fusiform gyrus. Languages that are more visually similar may produce a more consistent activation of the left VWFA.

Currently, little is known about the VWFA response to languages that use the same writing systems, but have different orthographies (e.g., Spanish and English; see, for example, Jamal et al., 2011). For speakers of languages, like English and Spanish, the early stages of word form recognition in each language are largely the same. First, the letter units are recognized. During this stage, minor differences in processing may include fine visual discriminations between accented and non-accented letters in Spanish. At the next stage of orthographic processing these speakers have to recognize syllables and syllable combinations. These more complex word-form elements have different

distributional properties across languages and, therefore, may require different processing channels, or different sets of representations. Finally, at the word form level, many more unique orthographic combinations have to be discriminated. If language tagging occurs at this stage, then two discrete word-form repositories have to be maintained for each language. If language tagging is postponed until later processing stages, then, even at this stage, there may still be significant similarity in the orthographic processing mechanisms required for same-script languages, like English and Spanish. This is so, because English and Spanish share approximately 15,000 words in terms of their orthography and meaning (Nash, 1997).

As early as during syllable recognition bilinguals' levels of proficiency in each language may influence neural activation. This influence becomes more pronounced during word form processing because of the different amounts of visual exposure to words in the more and less proficient languages. According to the functional specialization account, the VWFA should be differentially recruited during reading in first and second language. Specifically, if the VWFA becomes more active with increasing reading expertise, then the language, for which participants report a higher level of reading proficiency, should produce greater activity in the VWFA, relative to the lower proficiency language.

Rationale

Activation of the VWFA by First and Second Language Words

One aim of this dissertation research was to examine the nature of neural processing in the VWFA and to determine how particular language experience shapes

activation of the word-form reading system. To address this aim, Experiments 1 and 2 measured the VWFA activation in response to Spanish and English words in two groups of fluent Spanish-English bilinguals. It was predicted that the pattern of the VWFA activity across these languages would signal the type of orthographic processing it supports: from complete overlap of activity for English and Spanish if the VWFA responds to letter units to complete non-overlap if the VWFA maintains separate orthographic lexicons for each language. In case of a partial overlap, further study will be necessary to determine whether this indicates a response to sub-lexical or lexical units, as both types of units can have visually similar counterparts in English and Spanish.

Activation of the VWFA by cognates and homographs

A way to answer the question of whether the VWFA response is lexical or sublexical is to test whether it is sensitive to lexical-level characteristics, such as meaning. An additional advantage of such test is that it can help to reveal the degree of this area's functional specialization for processing orthographic word-forms. Experiment 3 did just that using words with a special status in the bilingual lexicon: *cognates* and *homographs*. Homographs share only word form in two languages, but not meaning (e.g., Eng. *pie* -Sp. *pie* [foot]). On the other hand, cognates share both orthographic form and meaning across two languages (e.g., Eng. *artist* - Sp. *artista*). Lexical processing by bilinguals is facilitated when both meaning and orthographic form are shared across the two languages. This is known as the *cognate facilitation effect* (e.g., Costa, Caramazza, & Sebastian-Galles, 2000). Conversely, when the orthographic form of a word in two languages is similar but the meaning differs, lexical recognition in bilinguals is impaired (Silverberg and Samuel, 2004; Von Studnitz & Green, 2002, but see Van Wijnendaele & Brysbaert, 2002). This type of impaired processing is often called the *homograph interference effect*.

The cognate facilitation and the homograph interference effects provide a means of testing the extent of lexical processing in the VWFA. If the VWFA processes only visual word form (be it whole word processing or syllabic processing), activation in this area should be similar for homographs and cognates. Specifically, the VWFA activity should demonstrate *adaptation* when either homograph pairs or cognate pairs are processed. We define adaptation as a decrease in the intensity of a neural response following presentation of identical stimuli (Chee, 2008). Using fMR-Adaptation (Grill-Spector & Malach, 2001; Henson, 2003) involves contrasting the blood-oxygenation level dependent (BOLD) signal for pairs of stimuli that are identical and pairs of stimuli that differ on some variable(s) of interest (Chee, 2008). Monolingual speakers of English show an adaptation response in the VWFA following repeated presentation of identical words and pseudowords (e.g., Glezer, Jiang, & Riesenhuber, 2009), as well as orthographically similar words (e.g., Devlin et al., 2006). For bilingual speakers, the presentation of pairs of homographs (e.g., Eng. *pie* - Sp. *pie* [foot]) should produce a similar decrease in neural activity in the VWFA relative to its activity during the presentation of pairs of unrelated and visually-dissimilar words. This decrease in neural activity of the VWFA should follow the presentation of pairs of cognates inasmuch as cognates share orthographic form. However, if the VWFA is sensitive to word meaning as well as to word form, then cognates and homographs might be expected to produce different patterns of activity in the VWFA, as only cognates share semantic similarity

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across two languages. Different response to cognates will also signal that the VWFA, likely, responds to whole words, since meaning is a lexical-level characteristic.

VWFA and the reading network

Another aim of this project was to examine the network of brain areas that may be working with VWFA during language processing. Although neural processing in the VWFA is often studied in isolation, reading involves concurrent activity in a number of brain areas supporting orthographic, phonological, semantic, and morphosyntactic processing. During reading, activity in anterior language areas, which process semantic and morphosyntactic codes may drive predictive responses in the VWFA. For example, Cornelissen and colleagues (2009) showed that MEG signals in the inferior frontal gyrus peaked at the same time as signals in the left middle fusiform gyrus, suggesting that there may be multiple reading pathways in the brain. The early activation of the left inferior frontal gyrus following presentation of word-like visual stimuli may help to prime the language system by initiating top-down anticipatory responses. The inferior frontal regions may also provide rapid feedback to the extrastriate language areas (such as the VWFA), indicating semantic and/or syntactic congruency in the input strings. Therefore, neural activity in the VWFA may reflect the combination of the visual input channeled from the occipital cortex and of top-down semantic/syntactic input from the frontal/temporal regions.

To understand the nature of neural processing in the VWFA, it may be necessary to consider how other brain areas modulate its processing. In the words of Price and Devlin (2003), if the function of the VWFA "depends on the interactions with other areas, then the neural correlates of that function can only be defined by specifying the set of interacting regions" (p.479). Consistently with this idea, previous studies of functional connectivity between brain areas revealed a network of regions involved in reading including left posterior fusiform gyrus (and parts of the VWFA), inferior frontal gyrus, and superior temporal gyrus (Mechelli et al., 2005). A similar set of areas was identified by Vinckier and colleagues (2007): the VWFA, Broca's area, superior temporal sulcus and supplementary motor area were all sensitive to the degree of stimulus similarity to real words. Therefore, studies that only focus on the activity in the VWFA may overlook important findings which may explain how interaction of the VWFA with other areas contributes to its function.

Experiment 3 supplements the findings from single word reading with the results of a graphical modeling algorithm carried out on the components of the reading network. These components were identified theoretically from previous neuroimaging work. Experiment 4 addresses the limitations of single word reading by using more ecologically valid sentence reading procedure in an attempt to account for the complexity of interactions that exist between linguistic codes.

Summary

A number of neuroimaging studies point to the important role that the VWFA plays in reading, yet the exact nature of neural processing in this part of cortex is currently a subject of an ongoing investigation. Whether the VWFA and other such areas within the inferior temporal lobe (e.g., Fusiform Face Area [e.g., Epstein & Kanwisher, 1998]; Parahippocampal Place Area [e.g., Maguire et al., 2001]; Extrastriate Body Area, Middle Temporal Gyrus Tool Area [e.g., Downing, et al., 2005], and others) exhibit functional specialization for processing a particular stimulus class is an important and timely question. It speaks to the notion of modularity of representations in this part of the brain and is fundamental to our understanding of the representational taxonomies that enable normal brain function. Practically speaking, this knowledge is valuable to a large spectrum of domains, from improved understanding of typical brain development in childhood to faster identification of impairments across patient populations.

In this dissertation research, I tested the VWFA response across two random samples of fluent bilingual speakers of English and Spanish, while these participants read words and sentences in their first and second language. A set of 4 experiments was designed to assess whether the VWFA responds to basic visual features, orthographic word forms, or lexical word forms and whether neural activity in this area is modulated by reading expertise. Experiments 1-3 were designed to reveal the characteristics of the VWFA response during single word reading. Experiment 4 measured the VWFA activity during sentence reading, as a way to uncover the role of this area within the language network.

Chapter 2: Univariate Analysis of the VWFA Response to English and Spanish Words in Fluent Bilingual Readers

Experiment 1: Introduction

Experiment 1 sought to establish the pattern of the VWFA activity in a group of fluent Spanish-English bilinguals, who differed in proficiency in their first and second language. Previous studies that looked at whole brain activity in Spanish-, French and Italian-English bilinguals found a broad similarity in the loci of activation across these languages when participants were making concrete/abstract judgments (e.g., Chee et al.,

1999; Illes et al., 1999), naming pictures (e.g., Hernandez, Martinez, & Kohnert, 2000), generating words (e.g., Klein et al., 1995), and listening to a story (e.g., Perani et al., 1996). Differences in neural activity were also observed as a function of age of acquisition (e.g., Isel et al., 2010; Kim, Relkin, Lee, & Hirsch, 1997; Dehaene et al., 1997) and proficiency (e.g., e.g., Meschyan & Hernandez, 2006; Perani et al., 1998). For example, differences in the activity of the left inferior frontal gyrus have been observed between speakers, who acquired a second language early in life, and speakers, who acquired a second language later in life (Kim et al., 1997; Wartenburger et al., 2003; Wattendorf & Festman, 2008). A lower-proficiency language was shown to recruit additional areas for processing (e.g., Abutalebi, Cappa, & Perani, 2001; Yetkin, Haughton, & Cox, 1996, but see Perani et al., 1996). For example, a PET study in English-French bilinguals revealed greater activation of the left putamen during word production in the lower-proficiency language, possibly due to increased articulatory demands (Klein et al., 1995). Recently, Jamal et al. (2011) also reported differences in neural activity for English and Spanish words in a group of Spanish-English bilinguals, who were matched for proficiency in both languages. In this study, English words activated prefrontal areas, including left middle frontal gyrus, to a greater degree, than Spanish words. In contrast, Spanish words activated left temporal areas more, than English words. The authors attributed such differences to greater consistency of orthography-to-phonology mapping in Spanish, than English. However, only lowfrequency words were used in this study, and for these words the role of orthographic transparency may be more prominent than for medium- or high-frequency words.

In this experiment, participants' proficiency level in each language was measured using a self-report questionnaire (see Appendix A), written word translation, and speed and accuracy during a word/non-word judgment task. It was expected that the outcome of this study will speak to the nature of neural processing in the VWFA. Specifically, a complete overlap of activity for English and Spanish in this group of bilinguals would be expected if the VWFA processes letter characteristics, as both of these languages rely on the same writing system (See Figure 2.2). A complete segregation of languages, either with respect to laterality of brain activation (left or right hemisphere) or within the VWFA in the left hemisphere would suggest that this region responds to whole word forms and maintains separate orthographic lexicons for each language. An intermediate case would imply that the VWFA processes either lexical or sub-lexical orthographic characteristics and that it uses the same neural populations to code for features overlapping across bilingual lexica.

Furthermore, any differences found in the VWFA activation as a function of language proficiency would support the notion that functional specialization in this area of cortex may develop as a function of growing expertise with orthographic stimuli.

Method

Participants

Eleven normal adult participants were recruited with flyers posted on New York University campus (9 women, 3 men, $M_{age} = 24.08$ years, *SD*=6.43 years). All participants had normal or corrected-to-normal vision and were judged to be right-handed using the Edinburgh Handedness Inventory (Oldfield, 1971). All participants reported being bilingual speakers of Spanish and English. One additional participant was excluded due to knowing a third language. The specific language profiles for all participants are described in Table 2.1. Participants granted a written informed consent to participate in the study in accordance with procedures approved by the New York University Human Subjects Committee. They received monetary compensation for taking part in the study.

Table 2.1: Language profiles for all participants, including age of first exposure, age of acquired fluency, proficiency and usage measures for each language.

	Native	Second	Language	AFE	AFE	AAF	AAF	DTE	DTE	DTU	DTU	DTU	TRP	TRP
	Language	Language	Preference	Spanish	English	Spanish	English	Spanish	English	Spanish	English	Mix	Spanish	EnglishNT
	Spanish/	Spanish/	Spanish/											
1	English	English	English	at birth	at birth	2	2	40%	60%	35%	65%	50%	100%	100%
			Spanish/											
2	Spanish	English	English	at birth	3	5	5	50%	100%	50%	50%	15%	100%	100%
3	Spanish	English	English	at birth	6	4	9	5%	95%	20%	70%	10%	67%	92% 11
			Spanish/											
4	English	Spanish	English	at birth	11	4	14	20%	80%	15%	85%	3%	100%	100% 23
5	Spanish	English	English	at birth	at birth	4	4	20%	98%	5%	95%	20%	67%	100% 14
6	English	Spanish	Spanish	3	at birth	22	3	50%	50%	25%	100%	25%	75%	100% 5
7	English	Spanish	English	at birth	at birth	5	5	15%	85%	10%	85%	15%	75%	100% 10
8	English	Spanish	English	at birth	4	19	4	10%	90%	25%	75%	100%	58%	83% 12
			Spanish/											
9	Spanish	English	English	at birth	5	2	6	25%	75%	50%	50%	25%	100%	92% 18
			Spanish/											
10	Spanish	English	English	at birth	4	2.5	5	20%	95%	20%	80%	15%	100%	75% 14
			Spanish/											
11	Spanish	English	English	at birth	4	2	21	70%	30%	60%	40%	0%	100%	100% 22

Note. Measures were collected using self-reports and translation. AFE – age of first exposure (in years); AAF – age of acquired fluency (in years); DTE – daily total exposure; DTU – daily total usage; TRP – total reported proficiency, including writing, reading and speaking; NT – number of correctly translated low-frequency Spanish nouns out of a total of 27 words.

<u>Materials</u>

To localize brain areas involved in processing English and Spanish words I presented participants with 3 sets of stimuli. The first set included 100 common English words, which were on average 5.44 letters long with frequency between 91 and 200 instances per million (IPM, Kucera & Francis, 1967). The second set consisted of 100 common Spanish words, which were on average 6.1 letters long with frequency between .04 and 882.91 IPM (Davies, 2002)¹. A complete list of word stimuli is provided in Appendix A. The third set of stimuli had 30 random checkerboard patterns, used to control for processing of basic visual features, such as lines, vertices, and patterns of black and white gratings (see Figure 2.1).



Figure 2.1: Sample stimuli.

(A) English words; (B) Spanish words; (C) checkerboard patterns. All stimuli were presented in black and gray on a white background.

¹ Differences in frequency between English and Spanish words are likely due to greater variability in Spanish frequency measures, which may be due to a larger corpus used to estimate the Spanish norms. Brown corpus used by Kucera and Francis (1967) has 1 million words and Corpus del Español used by Davies (2002) has 100 million words. In both languages, concrete and commonly used words were chosen.

Procedure

Images were presented using PyEPL software (Geller, Schleifer, Sederberg, Jacobs, & Kahana, 2007). Participants passively viewed the stimuli back-projected onto a screen and reflected in a mirror in the head coil of the fMRI scanner. Each stimulus appeared on the screen for 500 ms and was followed by a fixation screen for 150 ms.



Figure 2.2: Letter distribution across all word stimuli separated by language. The words used to measure the VWFA response to English and Spanish did not differ with respect to letter distributions. This was tested statistically using a Kolmogorov-Smirnov test (Birnbaum & Tingey,1951), which showed that the two samples of letters likely came from the same underlying distribution (D=.14, p=.95). Thus, any differences in the VWFA response to these stimuli cannot be accounted for by the differences in letter processing. Although Kolmogorov-Smirnov test is ordinarily used with continuous distributions, it produces robust estimates even with categorical data. A Chi-square test was not appropriate because many letters had frequencies lower than 5.

The order of stimulus presentation was randomized with replacement. Stimuli were presented in blocks of 20 trials separated by 8 s rest periods. There were 3 runs of 3 blocks each (English words, Spanish words, and checkerboard patterns). The order of blocks was randomly determined on each run.

fMR Image Acquisition

A 3T Siemens Allegra head-only fMRI scanner and Siemens standard head coil (Siemens) were used for data acquisition. Functional images were acquired using a single-shot gradient echo-planar EPI sequence (TR=2000 ms, TE=30 ms, flip angle = 90° , matrix = 64 x 64, FOV = 192 mm). Thirty-six contiguous oblique axial slices (3 x 3 x 3 mm voxels) parallel to the AC-PC line were obtained. Anatomical images were acquired using a T1-weighted protocol (TR=2500 ms, TE = 3.93 ms, matrix = 256 x 256, 176 1-mm sagittal slices).

fMRI Data Analysis

Image preprocessing and data analysis were performed using FSL 4.1 software (FMIRB's Software Library, <u>www.fmirb.ox.ac.uk/fsl</u>). The first 8 seconds of each scanning session contained instructions and were discarded. Functional images were high-pass filtered (Gaussian-weighted least-squares straight line fitting, with sigma = 60 s); skull stripped using BET (Smith, 2002); motion corrected (MCFLIRT [Jenkinson, Bannister, Brady & Smith, 2002]); and smoothed using a Gaussian kernel of FWHM 8 mm. The hemodynamic response function was modeled using a Gamma function (phase = 0 s, SD = 3 s, Mean lag = 6 s). All functional images were registered to high resolution anatomical and standard MNI (Montreal Neurological Institute) space images using FLIRT (Jenkinson and Smith, 2001; Jenkinson et al., 2002).

Whole brain neural activity during English or Spanish word presentation was contrasted with the checkerboard baseline. A two-level statistical analysis approach was used. Condition effects were first estimated in individual participants using FEAT (FMRI Expert Analysis Tool) first-level analysis. Individual participant *z* (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.00 and a (corrected) cluster significance threshold of p=.01. The results were then entered into a group-level analysis. The higher-level analysis was carried out using FLAME 1+2 mixed-effects analysis (Beckman, Jenkinson, & Smith, 2003). Group-level z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.96 and a (corrected) cluster significance threshold of p=.05 (Worsley, 2001).

To estimate the percentage of overlap between areas of activation for Spanish and English words, individual participants' *z*-statistic contrast images were masked by the temporal occipital fusiform gyrus mask from the Harvard-Oxford Cortical Atlas, available as part of the FSL software package (FMIRB's Software Library, <u>www.fmirb.ox.ac.uk/fsl</u>). Overlap percentage was measured as the number of significantly co-activated brain voxels in the contrasts English words vs. checkerboards and Spanish words vs. checkerboards relative to the total number of significantly activated voxels in these contrasts.

To measure the extent and strength of the VWFA response, group-level activity for Spanish and English, was compared directly. In addition, an analysis using Featquery (FMIRB's Software Library, www.fmirb.ox.ac.uk/fsl; Mumford, 2007) was performed on the group-level z (Gaussianised t/F) statistic images masked by the temporal occipital fusiform cortex mask. The number of active brain voxels and percent signal change for each contrast (English words vs. checkerboards; Spanish words vs. checkerboards) in the left temporal-occipital-fusiform cortex were obtained using this analysis. Percent signal change was calculated relative to the mean level of activity during the scan.

Results

Proficiency

As shown in Table 2.1 the majority of participants began learning Spanish as their first language ($M_{age of initial exposure} = .27$, SD = .9). Around the age of 4, about the time when children enter school, these participants began learning English ($M_{age of initial exposure} = 3.36$, SD = 3.38). The age, at which participants attained fluency varied, however most became fluent in both languages early in life ($M_{age of attained fluency in Spanish} = 6.5$, SD = 7.05; $M_{age of attained fluency in English} = 7.09$, SD = 5.66). Participants reported being exposed to English 78% (SD = 23%) of the time and to Spanish 30% (SD = 20%) of the time in a given day. They reported using English 72% (SD = 19%) of the time and Spanish 29% (SD = 18%) of the time in a given day. Interestingly, they also claimed to mix the two languages on average about 25% (SD = 28%) of the time. Their self-reported total proficiency in Spanish (including writing, reading and speaking) was somewhat lower (M = 86%, SD = 17%), than in English (M = 95%, SD = 9%). Participants were able to translate on average 14.33 (SD = 5.81) of 27 highly infrequent Spanish words into English.

In addition to self-report and translation scores, behavioral data on speed and accuracy of word recognition were collected for English and Spanish. These data are described in more detail in Experiment 3, however, it is worth noting that average reaction time during this task was slower for Spanish ($M_{RT} = 909.67 \text{ ms}$; SD = 219.56 ms), than for English stimuli ($M_{RT} = 785.38 \text{ ms}$; SD = 119.63 ms), t(10) = 3.08, p < .05. Accuracy was also lower for Spanish (M = .88, SD = .08) than for English (M = .96, SD = .05), t(10) = 4.78, p < .001. Together, the data from self-reports, translation and word recognition suggest that, at the time of study, participants' proficiency in their first
language was lower, than proficiency in their second language, perhaps owing to the fact that they were living in an environment, where English is the dominant language.

Activation Maps

The group-level analyses showed that participants activated similar brain areas during passive viewing of English and Spanish words as compared to the checkerboard pattern baseline. Left lateralized clusters of activity were found in the prefrontal and inferior temporal regions for both English and Spanish (see Figure 2.3 and Table 2.2).

More specifically, areas of activation were found in the left posterior middle temporal gyrus, lateral occipital cortex, middle and inferior frontal gyri and frontal orbital cortex. Both English and Spanish words activated the left inferior occipito-temporal regions, where the VWFA is located, but a greater extent of activity was found for Spanish, than for English in this area (see Figure 2.4). To quantify the differences in the extent of the VWFA activation the number of active voxels in the left temporal-occipitalfusiform cortex (including the VWFA) was measured for English and Spanish words. English words activated on average 249 voxels and Spanish words activated 569 voxels, *t* (7) = 2.76, p < .05.

Percent Signal Change

Spanish words modulated activity in the temporal-occipital-fusiform cortex to a greater degree than English words. Average percent signal change relative to the mean intensity baseline was .22 % (*SD*=.08) for English and .43 % (*SD*=.18) for Spanish, *t* (7) =2.34, *p*=.052. Figure 2.5 illustrates the timecourse of the VWFA activation by English

and Spanish words averaged across 3 stimulus presentation blocks. As shown in the figure, the amplitude of brain activity was greater for Spanish, than for English.



Figure 2.3: Areas of activation for English and Spanish words relative to checkerboard patterns. Group-level z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.96 and a (corrected) cluster significance threshold of p=.05. Here and in all subsequent figures brain slices were selected based on the average location of the center of the VWFA (x=-44, y=-58, z=-15; Jobard et al., 2003). Images are presented following the radiological convention (left- right orientations reversed).

Table 2.2: Peaks of activation during English and Spanish word reading vs. the checkerboard baseline.

Harvard-Oxford Cortical Structural Atlas Label	<i>z</i> -value	х	у	Z
Spanish Words vs. Checkerboards				
Left Occipital Pole	4.11	-26	-92	0
Left Lateral Occipital Cortex, superior	3.64	-34	-72	50

Intracalcarine Cortex	3.59	2	-80	4
Left lateral Occipital Cortex, inferior	3.54	-42	-80	-16
Left Inferior Frontal Gyrus, pars opercularis	3.5	-38	22	16
Left Occipital Fusiform Gyrus	3.45	-44	-68	-26
English Words vs. Checkerboards				
Left Middle Frontal Gyrus, posterior	3.69	-36	4	44
Left Inferior Frontal Gyrus, pars opercularis	3.28	-36	20	20
Left Precentral Gyrus	3.26	-52	-8	42
Left Middle Frontal Gyrus, anterior	3.22	-54	20	32
Left Frontal Pole	3.22	-40	44	2
Left Temporal Pole	3.21	-50	14	-22
Left Middle Temporal Gyrus, posterior	3.69	-62	-30	-6
Left Superior Temporal Gyrus, posterior	3.52	-64	-38	6
Left Middle Temporal Gyrus, posterior	3.35	-54	-38	-2
Left Middle Temporal Gyrus, posterior	3.35	-56	-42	-2
Left Middle Temporal Gyrus, temporooccipital	3.28	-60	-46	-2
Left Supramarginal Gyrus, posterior	3.26	-62	-44	10

Note. Each peak is described by a *z*-value, related to the intensity of activation and x, y, z coordinates in standard MNI brain space. Group-level *z* (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.96 and a (corrected) cluster significance threshold of p=.05.



Figure 2.4: Areas of increased activation for Spanish words relative to English words. Group-level z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.96 and a (corrected) cluster significance threshold of p=.05.



Figure 2.5: Time-course of neural activation in the left Temporal Occipital Fusiform Cortex (labeled according to Harvard-Oxford Cortical Atlas) across blocks of Spanish and English trials. Individual mean voxel time-series of neural activity were centered relative to each participant's mean activity in the experiment, averaged across participants, standardized relative to mean and variance and averaged across 3 presentations of blocked English and Spanish trials.

Individual Analyses

The group analysis of brain responses showed that Spanish and English words activated overlapping areas in this sample of bilingual speakers. Analysis at the individual level suggested that even though neural activity in the temporal occipital fusiform gyrus overlapped for the two languages, there were also some areas that were only activated by English words and other areas that are only activated by Spanish words (see Table 2.2).



Figure 2.6: Areas of overlap between brain activity for English and Spanish words relative to checkerboard patterns for 3 example participants.

Individual participants' z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.00 and a (corrected) cluster significance threshold of p=.01.

The percentage of overlap between these areas differed across participants (see Figure 2.6) and was related to the participants' bilingual proficiency. Specifically, the age, at which participants attained proficiency in English ($b_1 = -1.18$, t = -2.53, p = .052), and the number of correctly translated infrequent Spanish words ($b_1 = 1.28$, t = 2.73, p < .05) predicted the percentage of overlap between brain areas activated by Spanish and English words. The regression model using these variables as predictors accounted for 61% of the variability in the overlap scores, but was only marginally significant (*F* (2, 5)

= 3.89, p = .096), probably because the overlap data were only available for 8 participants.

Discussion

Results of Experiment 1 showed that when bilinguals read words in English and Spanish, they activated similar networks of left-lateralized brain regions. These regions included parts of the left occipito-temporal cortex, where the VWFA is located, and additional regions, including the left posterior middle temporal gyrus, left lateral occipital cortex, left middle and inferior frontal gyri and left frontal orbital cortex. These brain areas have previously been associated with language processing. For example, activity in the middle frontal gyrus was found during sentence comprehension and during singleword retrieval (see Price, 2010 for review). Stroke-related damage to the middle frontal gyrus was correlated with decrement in comprehension of syntactically-complex sentences (e.g., Dronkers et al., 2004). In bilingual speakers, who acquired their second language later in life, middle frontal gyrus became activated when they read translation equivalents in their first and second language (Isel et al, 2010). Taken together, these findings suggest that middle frontal gyrus is engaged during semantico-syntactic processing in both monolingual and bilingual speakers. In the present study, left middle frontal gyrus activity was likely related to semantic processing of English and Spanish words, as there were no sentences in our task.

Furthermore, parts of left inferior frontal gyrus have been implicated in different stages of language processing. The orbital part (BA² 47) was involved in semantic analysis (e.g., Jobard et al., 2003; Price, 2010; Vigneau et al., 2006 in monolinguals; Abel

²Brodmann Area-a region of cerebral cortex defined based on its cytoarchitecture

et al., 2009; Chee, Caplan, et al., 1999; Chee, Soon, & Lee, 2003; Klein et al., 2006; Illes et al., 1999 in bilinguals); sentence production (e.g., Kim et al., 1997 in bilinguals) and comprehension (e.g., Santi & Grodzinsky, 2007; Turken & Dronkers, 2011; Price, 2010 in monolinguals). The opercular (BA 44) and triangular (BA 45) parts are associated with phonological analysis, word-form encoding and articulatory planning (e.g., Abel et al., 2009; Fiez & Petersen, 1998; Indefrey & Levelt, 2004; Jobard et al., 2003; Price, 2010; Vigneau et al., 2006 in monolinguals). Some studies also suggest that the opercular and triangular parts of the left inferior frontal gyrus (BA 44/45) support verbal working memory (e.g., Fiebach et al., 2005). In our group of bilingual speakers, activation peaks for both English and Spanish words were found in the orbital part of the left inferior frontal gyrus, which corresponds to BA 47, suggesting that this activation was probably related to semantic, rather than phonological, or articulatory processing. Lateral occipital cortex is thought to hold object knowledge (e.g., Caramazza & Shelton, 1998) and its activation in our study may be related to processing of word meaning. Thus, consistently with previous research (e.g., Fiez & Petersen, 1998; Mechelli, et al., 2005; Vinckier et al., 2007) the brain areas supporting orthographic processing, including parts of the occipito-temporal cortex and the VWFA, were co-activated with brain areas, associated with processing of word meaning.

In this experiment, greater activation of the occipito-temporal cortex, including the VWFA, was found for Spanish, than for English words. Considering that participants showed lower proficiency in Spanish, than in English, these results indicate that the VWFA is more involved when language ability is low. This finding is in contrast with developmental evidence, which shows that ERP responses, associated with the VWFA, increase when children learn to read (Maurer et al., 2006). However, ERP signal carries limited information about the spatial extent of neural activity. Other brain imaging studies of reading-related tasks in children suggest that the age when reading skills are acquired is characterized by a shift in neural activity for words from bilateral extrastriate regions to predominantly left-lateralized occipito-temporal sites (e.g., Schlaggar et al. 2002, Shaywitz et al. 2002, Brown et al. 2005). This finding points to a reduction, rather than an increase, in the total activated area as reading skills improve. In adult literature, acquiring visual expertise during training has also been associated with a decrease in the activity of the VWFA (e.g., Xue & Poldrack, 2007), suggesting, perhaps, that as neural processing becomes more efficient, there is no longer a need to recruit large regions of cortex. In addition, many studies found transient decreases in the VWFA activation following repetition of the same stimulus. This phenomenon, called neural adaptation (Grill-Spector and Malach, 2001), may signal a short-term gain in neural efficiency as a function of experience.

One likely conclusion from these results is that in both children and adults increased reading expertise leads to fine-tuning of neural activations and a more localized VWFA response. Alternatively, recruitment of this area may differ for children and adults. An initial increase in the VWFA activity, as it comes online during childhood and adolescence, may be followed by a subsequent decrease in activity during adulthood. This decrease may be a part of global synaptic pruning which takes place as children transition into adulthood. During adulthood, the VWFA activity in skilled readers is both localized (e.g. Vinckier et al., 2007) and decreases in amplitude with increased familiarity (e.g., Xue & Poldrack, 2007). Consistently with this argument, the results from Experiment1 showed that the *higher*-proficiency language produced both a smaller extent of activation and a lower modulation of neural activity in the VWFA. The latter result is inconsistent with the notion that children and adults share the mechanisms of the VWFA activation, because ERP signals in children were shown to *increase* in amplitudes to words with increased reading skill (Maurer et al., 2006).

Group results from Experiment 1 confirmed that the VWFA activity is modulated by reading skill. Similarly, individual-level analyses revealed that the VWFA activation varied across participants as a function of proficiency. In all participants, English and Spanish produced activation of partially overlapping sets of brain voxels in occipitotemporal cortex. As discussed earlier, such pattern of activity indicates that similar orthographic processing mechanisms are employed by English and Spanish. This processing could either be carried out at the lexical or the sub-lexical level. Further experimentation is necessary to determine whether orthographic input is processed in this region in the form of whole words or as sub-lexical units. Interestingly, the degree to which activations for English and Spanish overlapped increased as the age of attained proficiency in English decreased and as participants' ability to translate infrequent Spanish words increased. Together, these predictors are related to participants' proficiency in Spanish and English, and this finding suggests that increased bilingual proficiency leads to greater convergence of brain activations for the bilingual's first and second language. This result is consistent with Green's (2003) convergence hypothesis, which poses that qualitative differences between first- and second-language neural processing disappear as proficiency increases.

Chapter 3: Multivariate Analysis of the VWFA Response to English and Spanish Words in Fluent Bilingual Readers

Experiment 2: Introduction

Experiment 1 provided an initial assessment of neural activation of the VWFA in fluent same-script bilinguals. General Linear Model (GLM) analysis employed in Experiment 1 revealed partially overlapping regions of activity for Spanish and English words in this part of cortex, suggesting that these two languages rely, in part, on the same orthographic processing mechanisms. Moreover, it was found that additional distinct neural populations may be used for each language, especially in bilinguals with lower English or Spanish proficiency.

GLM analysis often overestimates the contribution of individual brain voxels to a condition of interest, because in this analysis individual voxels are treated as independent. A convergent method of analysis was sought; one that would provide improved estimates of voxel distributions for English, Spanish and their overlap by utilizing covariance across voxels. One such group of methods is referred to, collectively, as multivariate (or multivoxel) pattern analysis (MVPA) (e.g., Poldrack, Mumford, & Nichols, 2010). MVPA has been used to better estimate voxel covariation and its diagnostic contribution to a condition of interest (e.g., Hanson, Matsuka, Haxby, 2004). Thus, MVPA *classifiers* are often known to increase the accuracy of the parameter estimates.

MVPA classifiers include a number of methods, such as neural networks (NN), support vector machines (SVM), and linear discriminant analysis (LDA). These classifiers find a relationship between a set of predictors and a categorical response. Some of these are better suited for cases with many correlated predictors and few observations, which are characteristics often ascribed to image and fMRI data. One such method was proposed by Whitten and Tibshirani (2011). This method, called penalized linear discriminant analysis (PLDA), is a penalized form of Fisher's LDA. It can often improve the estimates even with very high covariance amongst the underlying variables. It has the advantage of not only producing high classification rates, but also providing linear weights/coefficients for each voxel, which makes it especially useful for interpretation.

A key advantage of the MVPA methods, like the PLDA, over the standard GLM analysis, is that one can assess their generalization (e.g., Poldrack, Mumford, & Nichols, 2011). This is accomplished by creating a classifier model on one set of data and then testing this model on another set of held out examples. This procedure is called *k*-fold *cross-validation*, where k stands for the number of separate trial blocks in the data. On each run of the classifier, one randomly-selected block of trials is held out and then used for testing the generalization of the classifier model. This is repeated multiple times, such that each block has a chance of being selected for cross-validation. The crossvalidation procedure requires that there are sufficient number of trial blocks in the data to both train and test the model. In Experiment 1, fMRI data were acquired for only 3 blocks of English words, Spanish words and checkerboards. This limited the number of examples that could be used to create the classifier model. In Experiment 2, a new set of fMRI data was collected, in which the number of trial blocks was increased to 5. This enabled the use of a 5-fold cross-validation procedure without any significant loss of accuracy in the model fit.

The main goal of Experiment 2 was to validate findings obtained in Experiment 1. A MVPA analysis was employed to determine if the recorded pattern of brain activity in the VWFA was diagnostically related to the different language conditions. In addition, I sought to verify that the samples of voxels with high sensitivity to each language overlapped in terms of their brain location.

In addition, a few procedural changes were made in Experiment 2. First, the number of bilingual participants tested in Experiment 2 was increased to 12, bringing the power of our multiple regression tests to 91%. This made it more likely that a statistically significant relationship between proficiency and VWFA overlap estimates would be found. Minor changes were also made to the stimuli and procedure with the goal of increasing the uniformity of the test materials and adjusting the experimental design for the maximum impact of the stimuli on brain activation. Moreover, the assessment of the bilingual language profile was revised to include more standardized and validated measures of proficiency and more detailed self-report questions.

Method

Participants

A separate group of 12 fluent Spanish-English bilinguals was recruited for this experiment using flyers posted on Rutgers University campus. These bilinguals acquired Spanish as their first language and English as their second language. They reported being first exposed to Spanish at birth and to English at the age of 5.2 (SD = 3.03). Most participants received early schooling in Spanish or a combination of Spanish and English. Participants reported becoming fluent in Spanish at the age of 4.21 (SD = 1.8) and in

English at the age of 6.79 (SD = 2.74). They could read single words in Spanish at the age of 6.75 (SD = 4.25) and in English at the age of 7.08 (SD = 2.27). They could read a newspaper in Spanish at the age of 9.79 (SD = 4.23) and in English at the age of 9.92 (SD = 4.14). Participants reported that they spent on average 4.67 years (SD = 6.33) in a country where Spanish was spoken and 17.75 years (SD = 4.96) in a country where English was spoken. Details on the individual participant profiles are provided in Table 3.1. All participants granted a written informed consent to participate in the study in accordance with procedures approved by the Rutgers University Institutional Review Board for the Protection of Human Subjects in Research. They received monetary compensation for taking part in the study.

Gende	Dominant Language	Education (4-7y)	AFE Spanish	AFE English	AEAF Spanish	AEAF English	DTE Spanish	DTE English	SRRP Spanish	SRRP English	PE Spanish	PE English	ALD Spanish
			-	-	-	-	-	-	-	-	-	-	
1 female	Spanish	Spanish	1	12	2	13	52%	48%	10	10	78.95%	76.60%	79%
2 female	English	Spanish	1	5	2	6	50%	50%	9	10	84.21%	87.23%	79%
3 Male	English	English, Spanish	1	3	5	5	30%	70%	7	10	89.47%	97.87%	77%
4 female	English	Spanish	4	5	7	5	40%	60%	5	2	53.95%	72.34%	69%
5 female	English	English	0	2	2	3	30%	70%	7	10	86.84%	91.49%	74.50%
6 Male	English	English	2	5	4	6	50%	50%	6	9	80.26%	89.36%	79%
7 female	English	Spanish	0	6	5	7	50%	50%	9	10	93.42%	95.74%	84.50%
8 female	English	Spanish, English	1	6	7	7	50%	50%	6	10	52.63%	78.72%	66%
9 female	English	Spanish	0	8	5	11	45%	50%	9	10	92.11%	89.36%	83%
10 Male	English	Spanish 4 English 5-7	y 0	4	4	5	25%	75%	8	10	93.42%	95.74%	85%
11 female	English	Spanish	1	6.5	2.5	7.5	40%	60%	6	10	82.89%	82.97%	72.50%

Table 3.1: Language profiles for all participants, including age of first exposure, age of early acquired fluency, and proficiency measures for each language.

12 female	English	English	1	0	5	6	50%	50%	6	7	85.53% 72.34% 79.50%
	0 -	0 -									

Note. Measures were collected using self-reports and proficiency tests. AFE – age of first exposure (in years); AEAF – age of early acquired fluency (in years); DTE – daily total exposure; SRRP - self-rated reading proficiency (1-10); PE – proficiency exam, grammar and comprehension; ALD – accuracy of lexical decision.

<u>Materials</u>

The stimuli used in this experiment were the same as in Experiment 1, except all words and checkerboard patterns were presented in white on a black background in order to increase the visual uniformity of the stimuli. The number of different checkerboard patterns was increased to 100. Prior to the imaging session, participants filled out a language experience and use questionnaire (adapted from Marian, Blumenfeld, & Kaushanskaya, 2007). A copy of the questionnaire is provided in Appendix B. They also completed a word recognition test in Spanish (adapted from Fairclough, 2011) and two proficiency tests evaluating grammar and comprehension in English and Spanish. The proficiency tests were those used by the Rutgers University's Department of Spanish and Portuguese Studies for student placement in advanced Spanish courses.

Procedure

The same procedure was followed as in Experiment 1, except that each stimulus appeared on the screen for 1000 ms (instead of 500 ms) with the same inter-stimulus interval of 150 ms. Stimuli were presented in blocks of 20, separated by rest periods of 8 s each. A total of 5 blocks of each stimulus category was shown. Participants were instructed to pay attention to the stimuli.

fMR Image Acquisition

A 3T Siemens Magnetom Trio Tim syngo MR B17 full body fMRI scanner and Siemens standard 32 channel head coil (Siemens) were used for data acquisition. Functional images were acquired using a single-shot gradient echo-planar EPI sequence (TR=2000 ms, TE=30 ms, flip angle = 90°, matrix = 64 x 64, FOV = 192 mm, distance factor = 33%, phase encoding direction = Anterior to Posterior) with a Prescan Normalize filter. Thirty-six contiguous oblique axial slices (3 x 3 x 3 mm voxels) parallel to the AC-PC line were obtained. Anatomical images were acquired using a T1-weighted protocol (TR=1900 ms, TE = 2.52 ms, matrix = 256 x 256, 176 1-mm sagittal slices).

fMRI Data Analysis

Image preprocessing and data analysis were performed in accordance with procedures used in Experiment 1. The first 4 seconds of each scanning session were discarded from the analyses. Functional images were high-pass filtered (Gaussian-weighted least-squares straight line fitting, with sigma = 100 s); skull stripped using BET (Smith, 2002); motion corrected (MCFLIRT [Jenkinson, Bannister, Brady & Smith, 2002]); and smoothed using a Gaussian kernel of FWHM 5 mm. The hemodynamic response function was modeled using a Gamma function (phase = 0 s, SD = 3 s, Mean lag = 6 s). All functional images were registered to standard MNI (Montreal Neurological Institute) space images using FLIRT (Jenkinson and Smith, 2001; Jenkinson et al., 2002).

Region of interest (ROI) analysis was performed by contrasting neural activity during English or Spanish word presentation with neural activity during checkerboard presentation within the temporal occipital fusiform mask from the Harvard-Oxford Cortical Atlas, available as part of the FSL software package (FMIRB's Software Library, <u>www.fmirb.ox.ac.uk/fsl</u>). A two-level statistical analysis approach was used. Condition effects were first estimated in individual participants using FEAT (FMRI Expert Analysis Tool) first-level analysis. Individual participant *z* (Gaussianised *t/F*) statistic images were thresholded using clusters determined by *z*>1.00 and a (corrected) cluster significance threshold of *p*=.05. The results were then entered into a group-level analysis. The higher-level analysis was carried out using FLAME 1+2 mixed-effects analysis (Beckman, Jenkinson, & Smith, 2003). Group-level *z* (Gaussianised *t/F*) statistic images were thresholded using clusters determined by *z*>1 and a (corrected) cluster significance threshold of *p*=.05 (Worsley, 2001).

Timeseries of activation were extracted from each participant's registered and skull-stripped fMRI data using individual *z*-statistic images for ROI definition. The timeseries of activation for each voxel were cross-indexed with condition labels using (PyEPL recorded) scanner pulse timestamps and stimulus onset timestamps. The 12 resulting matrices (N trials x N active voxels) were submitted to the principle components analysis (PCA) in order to reduce the number of the underlying stimulus dimensions (e.g., Mardia, Kent, Bibby, 1979). The first principal component or the first two principal components were not used for further analysis, this removed noise and large linear trends in the data, which were unrelated to the experimental design. The resulting matrices (N trials x N principal components) were used in the PLDA analysis. The PLDA was run 100 times, with average accuracies aggregated across the 100 runs. For generalization testing a 5-fold cross-validation procedure was used. All classifier analyses were performed using the statistical software R (R development core team, 2009; http://www.R-project.org) and its contributed packages AnalyzeFMRI (Marchini &

Lafaye de Micheaux, 2009), MASS (Venables & Ripley, 2002), and PenalizedLDA (Whitten & Tibshirani, 2011).

Results

Proficiency

Only one participant identified Spanish as their dominant language, all other participants reported English as more dominant. When asked to self-identify as having an accent in Spanish, participants reported having very light to light accent, whereas in English they reported having none to almost none. They rated the frequency of being identified by others as a non-native speaker of Spanish as 2.83 out of 10 (SD = 2.74) and a non-native speaker of English as 1.25 out of 10 (SD = 1.76), where 0 corresponded to "never", 5 was "half of the time" and 10 was "all of the time". Participants' self-rated reading proficiency was on average 7.33 (SD = 1.61) out of 10 in Spanish and 9 out of 10 (SD = 2.37) in English. Participants used a rating scale where, 7 corresponded to "Understanding parts of abstract and complex texts" and 9 was identified with "Being able to read literary texts, editorials and technical texts". Participants scored on average 85.81% correct (SD = 9.09\%) on an English grammar and comprehension test and 81.14% correct (SD = 13.86\%) on a Spanish test. They also scored on average 77% correct (SD = 5.9%) on a word recognition test in Spanish. These results indicate that all participants were highly proficient in both of their languages, with a moderate proficiency advantage for English.

Activation Maps

As in Experiment 1, the GLM analysis applied to the data in Experiment 2, revealed regions of activation, which overlapped for English and Spanish words and regions, which were uniquely recruited by each language. The overlapping regions represent the parts of the VWFA where voxels responded equally well to English and Spanish words. These voxels collectively embody what we have descriptively dubbed as the "Spanglish" area (see Figure 3.1 for illustration).



Figure 3.1: Areas of activation for English and Spanish words relative to checkerboard baseline. Individual participants' z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.00 and a (corrected) cluster significance threshold of p = .05.

Individual participants varied in the degree of overlap between their English and Spanish-activated voxels. The range for the proportion of "Spanglish" voxels relative to the total number of active voxels in the VWFA was 94.33%, with the minimum of 2.37% in participant 3 and a maximum of 96.7% in participant 9. The median proportion of overlapping voxels was 54.78 % (SD = 33.35%). The relationship between the standardized proficiency measures and overlap scores did not reach significance in the multiple regression analysis. All participants scored high on the proficiency measures with a very narrow margin of error. This suggested that the standardized measures may

have lacked in sensitivity when measuring proficiency in this group of bilingual speakers. The self-reported proficiency characteristics such as age of acquisition also did not correlate with overlap scores; all participants acquired both languages early in life. As was the case with standardized proficiency measures, these self-report variables did not span over the whole range of possible language acquisition profiles.

Multivariate Pattern Analysis: Penalized Linear Discriminant

The PLDA was run 100 times in each participant. During every run, one of 5 stimulus blocks was randomly selected for cross-validation. This block was not used for training the classifier model. Accuracies for each group were aggregated across all 100 runs and subsequently averaged. Mean training accuracy was above 75% for all participants and all conditions. Cross-validation accuracy was measured by testing the PLDA model on the held out block of stimuli. The model predicted category membership (Spanish or English word vs. checkerboard pattern) based on the pattern of brain activity in this block. The PLDA model produced good cross-validation accuracy in all but 2 participants (9 and 11). For one additional participant cross-validation accuracy was close to chance on English trials and above chance on Spanish trials (see Table 3.2). Statistical significance of the cross-validation accuracy was evaluated using the binomial probability test. This test evaluated the alternative hypothesis that the true probability of success is not equal to .5. This number represents chance in a 2 alternative-forced choice paradigm (e.g., English vs. checkerboard baseline). Excluding the 3 participants mentioned earlier, cross-validation accuracy was found to be significantly above chance in all participants. The predictive power of the classifier model was also tested against a theoretical null distribution. This distribution was

derived for each participant by running the cross-validation procedure 100 times with trial labels randomly intermixed. The cumulative density graphs for the null and alternative distributions are provided in Figure 3.2.

 Table 3.2: PLDA accuracy and standard errors across participants during training and

cross-validation.

						-		
		Tra	ining		Cross-va	alidation		
S#	English	Checker	Spanish	Checker	English	Checker	Spanish	Checker
1	.95(.002)	.94(.002)	.94(.003)	.86(.003)	.83(.01)	.79(.02)	.71(.02)	.71(.03)
2	.87(004)	.88(.004)	.94(.002)	.95(.003)	.59(.02)	.61(.02)	.78(.02)	.75(.02)
3	.95(.003)	.87(.003)	.96(.003)	.94(.002)	.75(.02)	.64(02)	.81(.01)	.65(.03)
4	.93(.003)	.95(.002)	.98(.002)	.91(.002)	.64(.02)	.66(.02)	.81(.01)	.83(.01)
5	.83(.003)	.87(.005)	.92(.004)	.90(.003)	.52(.02)	.64(.02)	.68(.03)	.63(.02)
6	.96(.003)	.86(.005)	.92(.003)	.96(.002)	.63(.02)	.56(.03)	.74(.02)	.69(.02)
7	.90(.003)	.97(.002)	.90(.006)	.91(.003)	.65(.02)	.71(.03)	.81(.01)	.64(.02)
8	.93(.004)	.94(.003)	.88(.003)	.97(.003)	.73(.03)	.73(.03)	.69(.02)	.68(.02)
9	.78(.005)	.83(.005)	.70(.006)	.84(.005)	.54(.02)	.56(.02)	.52(.03)	.51(.03)
10	.89(.003)	.98(.002)	.91(.003)	.96(.003)	.62(.03)	.60(.02)	.69(.02)	.75(.03)
11	.85(.003)	.85(.003)	.86(.002)	.91(.005)	.62(.01)	.57(.02)	.73(.01)	.58(.03)
12	.93(.003)	.96(.002)	.88(.002)	.94(.003)	.69(.03)	.65(.03)	.70(.01)	.63(.02)
Mean	0.90(.02)	0.91(.02)	0.90(.02)	0.92(.01)	0.65(.03)	0.64(.02)	0.72(.02)	0.67(.02)
Mean	0.90(.02)	0.91(.02)	0.90(.02)	0.92(.01)	0.65(.03)	0.64(.02)	0.72(.02)	0.67(.02)

Table 3.3: Results of the binomial probability test assessing classifier cross-validation accuracy.

	Cross-validation									
S#	English	Checker	Spanish	Checker						
1	p <.0000000005;	p <.00000005;	p <.00005;	p <.00005;						
	95% CI (.7490)	95% CI (.7087)	95% CI (.6180)	95% CI (.6180)						
2	p < .09;	p < .05;	p <.00000005;	p < .0000005;						
	95% CI (.4969)	95% CI (.5171)	95% CI (.6986)	95% CI (.6583)						
3	p < .0000005;	p <.01;	p <.000000005;	p <.005;						
	95% CI (.6583)	95% CI (.5473)	95% CI (.7288)	95% CI (.5574)						
4	p <.01; CI	p <.005;	p <.000000005;	p <.0000000005;						
	95% (.5473)	95% CI (.5675)	95% CI (.7288)	95% CI (.7490)						
5	p = .76;	p <.01;	p <.0005;	p <.05;						
	95% CI (.4262)	95% CI (.5473)	95% CI (.5877)	95% CI (.5372)						
6	p <.05;	p =.27;	p <.000005;	p <.0005;						
	95% CI (.5372)	95% CI (.4666)	95% CI (.6482)	95% CI (.5978)						
7	p <.005;	p <.00005;	p <.000000005;	p <.01;						
	95% CI (.5574)	95% CI (.6180)	95% CI (.7288)	95% CI (.5473)						
8	p <.000005;	p <.000005;	p <.0005;	p <.0005;						

	95% CI (.6381)	95% CI (.6381)	95% CI (.5978)	95% CI (.5877)
9	p =.48;	p =.27;	p =.76;	p =.92;
	95% CI (.4464)	95% CI (.4666)	95% CI (.4262)	95% CI (.4161)
10	p <.05;	p <.06;	p <.0005;	p < .0000005;
	95% CI (.5272)	95% CI (.5070)	95% CI (.5978)	95% CI (.6583)
11	p <.05;	p =.19;	p <.000005;	p = .13;
	95% CI (.5272)	95% CI (.4767)	95% CI (.6381)	95% CI (.4868)
12	p <.005;	p <.005;	p <.00005;	p <.001;
	95% CI (.5574)	95% CI (.5574)	95% CI (.6281)	95% CI (.5776)

Note. CI - confidence interval.

For each language, the distributions illustrated in Figure 3.2 were compared using the Kolmogorov-Smirnov test (Birnbaum & Tingey, 1951), which showed that the null and alternative distributions were statistically different (Spanish: D=.48; p <.001; English: D=.31, p<.001). From the figures it appears that the VWFA response in these bilinguals is more sharply tuned to Spanish, although this could be due to undersampling.

The PLDA model of neural responses in the VWFA was considered to be both valid and reliable, because a good model fit and above-chance cross-validation accuracy were observed in all, but 2 participants. The indices of voxel sensitivities were obtained from the model as a way to represent the landscape of the VWFA activation to Spanish and English words, as well as to determine where these neural responses overlapped, i.e., find the so called "Spanglish" area. The PCA weights from the linear discriminant functions of the PLDA were first converted to absolute values (to equally weigh high positive and high negative weights)³ and then averaged across 100 runs of the PLDA.

³ Each run of the PLDA could have arrived at a different linear discriminant equation. Consequently, a given component could carry a high positive or a high negative weight across instantiations of the model. When averaged, these values would produce a weight near zero, which would not reflect the true contribution of the component to the accuracy of the classification. To leverage this problem all weights were converted to absolute values prior to averaging. The downside of this conversion is that the sum of voxel activations scaled by their weights no longer reflected the true value predicted by the model, however, in this part of the analysis the focus was on the individual voxels and not on classification accuracy.



Figure 3.2: Cross-validation accuracy under null and alternative hypotheses. Actual PLDA cross-validation accuracy combined across participants compared against a theoretical null distribution, created for each participant by randomly intermixing condition labels during cross-validation.

The component weights were then used to scale voxel activation values (by calculating the dot product of the observation matrix and the weight vector). This was done to obtain each voxel's sensitivity to the experimental conditions.

The voxels with high resulting activation values were considered to be critical for discriminating the type of visual input that the participant was exposed to: English words, Spanish words or Checkerboards. The voxels with activation values near zero were considered to be less critical. This is because, in a linear equation, such as the one below, each variable's contributions are summed to arrive at an outcome:

$$Y = \omega_0 + \omega_1 x_1 + \omega_2 x_2 + \dots + \omega_n x_n$$

Similarly, in a linear discriminant analysis, a large weight would put an observation clearly on one side of the hyperplane separating the classes, whereas a small weight would put it on the border between classes.

Measures of overlap were estimated by pooling all of the voxel weights across participants and selecting the weight values which corresponded to the z scores of 2 and -2. Each participant's data was then examined and all weights that were above the upper weight value from the group data (z=2) and below the lower weight value (z=-2) were chosen. This represented top 5% of voxels in terms of their sensitivity. The number of voxels that were the same in the top 5 % of most sensitive English voxels and the top 5 % of most sensitive Spanish voxels were counted as overlap voxels. A more inclusive measure of overlap was also calculated using z=1 and z=-1, where the selected weights represented about 26% of the underlying distribution. These voxels weights were then projected into a 91 x 109 x 91 matrix and mapped onto a standard MNI152 T1-weighted brain template (available as part of the FSL software package; FMIRB's Software Library, <u>www.fmirb.ox.ac.uk/fsl</u>). Each voxel's position was preserved in the analysis, such that the reconstructed voxel activations were located in the same position as the original input voxels. The resulting images are shown in Figure 3.4. As with GLM results, clusters of voxels sensitive to a single language and clusters jointly sensitive to English and Spanish were observed. Among the top 26% of most sensitive voxels, an average of 27.50% (*Median*= 25.10%; *SD* = 12.84%) overlapped for English vs. checkerboard and Spanish vs. checkerboard classifications. The minimum overlap was 12.88% and the maximum was 62.79%.

When measures of overlap were estimated using PLDA, instead of GLM, a significant relationship was found between the self-reported ages of language acquisition and the percent of overlapping voxels (multiple linear regression: F(2, 9) = 10.00, p < .01). Specifically, greater percent overlap in the VWFA was associated with increased age of acquired fluency in English ($b_1 = 1.96, t = 4.28, p < .005$) and lower age at which participants became able to read single words in English ($b_1 = -1.55, t = 3.38, p < .01$).

Both estimates of overlap (among top 5% and top 26% of voxels) showed a significant relationship with the age of acquisition measures, suggesting that the multivariate analysis in this case provided greater sensitivity in detecting brain-behavior correlations. (Importantly, the same kind of relationship between the age of attained English fluency, proficiency measures in Spanish and percent overlap in the VWFA were found in Experiment 1). Figure 3.3 represents a three-dimensional regression surface between percent of overlap and the two self-report measures of age of acquisition.





The earlier participants started reading in English (in years of age) and the later they attained English fluency (in years of age) the bigger was the overlap region.

Discussion

Our analyses indicated that unlike English and Chinese (e.g., Perfetti et al., 2007), English and Spanish are encoded by partially overlapping areas in the inferior occipitotemporal cortex, where the VWFA is found. Significant overlap of activations for English and Spanish in fluent bilingual speakers may be a result of repeated application of similar orthographic *processes* during word recognition in these languages. English and Spanish may also rely on shared *representations* of overlapping orthographic elements.

English and Spanish utilize the same writing system and, therefore, have a number of syllables, syllable combinations and words that are orthographically identical.



Figure 3.4. Top 26% of voxel weights that contributed to PLDA classification accuracy. Weights are superimposed on the MNI152 T1-weighted standard template according to radiological convention.

Yet, there are also some letter clusters that are common in one language, but never occur in the other language (e.g., English: *ght*; Spanish: *ll*); and there may be distinct orthographic processes involved in recognition of words in English and Spanish. For example, one such process may be related to rapid recognition of words with common letter shape (e.g. *apple*, *spade*, *quite*, *ample*). According to Pelli and Tillman (2007), identification of word shape can explain up to 16% of the variance in reading. Languages differ with respect to common letter shapes, in part due to the differences in syllable structure. For example, English has a lower frequency of open (consonant-vowel) syllables, than Spanish, and a higher frequency of closed (consonant-vowel-consonant) syllables and syllables with compound consonant clusters (e.g., *straight*; Davies, Cuetos, & Gles-Seijas, 2007). This surface orthographic difference produces greater orthographic complexity in English, relative to Spanish, and leads to slower acquisition of reading fluency in English-speaking children (e.g., Seymour et al., 2003). It is also related to a deeper dichotomy between English and Spanish, which concerns the amount of interaction between orthographic processes and pre-lexical phonological processes (Rapp, Folk & Tainturier, 2001). Spanish may rely more on the pre-lexical orthographyto-phonology mapping during reading, whereas English may require a greater amount of lexical mediation, due to a large number of exception words (e.g. Jamal et al., 2011).

These orthographic processes, by no means, encompass the full breadth of differences and similarities between English and Spanish in terms of their orthographic codes. Yet, they help to explain the existence of both distinct and of overlapping neural populations for reading in English and Spanish, which were observed in the bilinguals' VWFA.

The unique contribution of this experiment to the overall project is in that it replicated the GLM results obtained in Experiment 1, and validated them using MVPA. The time series of activation obtained from the VWFA provided sufficient information to reliably distinguish between English and Spanish words when they were compared to checkerboard patterns. But the activity observed in the VWFA does not show a complete segregation of orthographic codes for each language. In contrast, this region seems to maintain some redundancy in representing orthographies that are visually similar. It distinguishes between these orthographies using graded patterns of activations. This follows from 3 pieces of evidence that were gathered in Experiments 1 and 2: (1) English and Spanish words activated overlapping sub-regions in the VWFA; (2) Each language also activated distinct sub-regions in the VWFA, even though the word stimuli used in the experiments did not differ with respect to their letter distributions (3) PLDA was able to reliably predict stimulus category given all candidate voxels in the VWFA and relied on partially different subsets of voxels when predicting English and Spanish category membership. If the response in the VWFA was tuned to any lexical stimulus relative to any picture stimulus, then the voxel populations distinguishing between Spanish words vs. checkerboards and English words vs. checkerboard should have been nearly identical. The same reasoning applies with respect to the VWFA response to letters: the activity in this region should have been the same for English and Spanish if it is functionally tuned to single letters. It is possible, that the non-overlapping regions of activity in the VWFA maintain language-related distinctions.

It's not yet clear from these results whether the representations in the VWFA are lexical or sub-lexical. In other words, this area could represent either whole word forms or just letter clusters, both accounts are plausible given these data. One relevant piece of evidence addressed in Experiment 3 will speak to whether this region is sensitive to lexical-level variables such as word meaning.

The results of Experiment 2 showed that the age of second language acquisition and reading onset predicted the VWFA landscape. Specifically, self-reported age of acquiring English fluency was positively associated with percent overlap. This behavioral measure not only represents the age, at which participants became fluent in English, but is also related to the amount of early exposure to Spanish and early Spanish fluency. Moreover, self-reported age of English reading onset was negatively associated with percent overlap. Overall, these findings are consistent with the notion that experience in reading modulates the VWFA activation. They show that while this area supports reading in English and Spanish, it treats words in these two languages as if they come from a common word distribution (or two partly overlapping distributions), especially in participants who had sufficient exposure to the first language and rapidly gained fluency and began reading in the second language. In essence, this is consistent with Green's (2003) convergence hypothesis, but here, the convergence hypothesis is extended to encompass age of acquisition, in addition to proficiency.

In Experiment 2, unlike Experiment 1, I didn't find a relationship between the patterns of the VWFA activation and language proficiency measures. This may be because the participants in Experiment 2 had more uniform proficiency profiles than those in Experiment 1. Consistently with this hypothesis, our standardized measures of proficiency in Experiment 2 showed range compression compared to the proficiency metric in Experiment 1: the translation task in Experiment 1 yielded low accuracy scores

with large variability across participants and the more standardized placement exams and lexical decision task in Experiment 2 produced higher overall accuracy and low variability measures. However, given significant similarities in the ages of acquisition and amounts of exposure to each language for participants in these two experiments, it seems unlikely that they would end up with very different language proficiency profiles. It's far more plausible that the standardized measures used in Experiment 2 were not diagnostic of participants' language proficiencies. Therefore, in future studies a more difficult test of proficiency may be necessary for fluent bilinguals, such as those who took part in Experiments 1 and 2.

It is important to acknowledge potential caveats in the provided interpretation of results, specifically, that the obtained pattern of brain activity is indicative of partially overlapping neural representations for first and second language. A well known limitation of the fMRI data is its poor spatial resolution. The consequence of this limitation is an uncertainty in the position of single voxels across time periods. This problem is compounded by the variation in the location of functionally specialized regions across participants. In the present analyses, an attempt was made to address these problems. Poor spatial resolution is leveraged by a number of pre-processing steps, such as motion correction and smoothing (averaging adjacent voxel activations). Care was also taken during spatial registration of each participant's brain data to the standard anatomical template. The differences in the location of the VWFA across participants were addressed by supporting group-level analyses with findings from each individual. Despite all of this, some residual variability in the spatial distribution of voxels may persist in the form of noise. However, the confidence in the present analysis is boosted by the reliability of the findings across two experiments and two bilingual samples. In Experiment 3, I continue to address these concerns by supporting traditional localization analyses with a connectivity analysis, which uncovers coherent patterns of joint variation in regional brain activity.

Chapter 4: Modeling Activation and Effective Connectivity of VWFA in Spanish-English Bilinguals

Experiment 3: Introduction

In speakers of a single language, reading words in their native language reliably activates the VWFA, regardless of the language or the writing system, as suggested by a recent meta-analysis of reading studies by Bolger and colleagues (2005). As shown by the findings of Experiment 1 and 2, Spanish-English bilinguals also recruit the VWFA for orthographic processing in their first and second language. Moreover, there is considerable overlap in the activation for English and Spanish within the VWFA, which suggests that these languages may rely on similar orthographic processes. It may be more so, for cases when word forms in these languages are visually similar. Recall, that when bilinguals were reading in two visually distinct languages, such as Chinese and English, they activated bilateral posterior fusiform gyrus (e.g., Perfetti et al., 2007), whereas Experiment 1 showed left-lateralized activations for English and Spanish, and these languages rely on the same writing system. If activation overlap increases with increased orthographic similarity, familiar word forms that are visually similar across two languages of a bilingual should evoke similar patterns of activation in this brain region. For languages such as English and Spanish, this may occur quite frequently, because

approximately 15,000 English words share orthography and meaning with their Spanish counterparts (Nash, 1997).

Words that are similar in orthography (homographs) and those that are similar in both orthography and meaning (cognates) across two languages have a special status in the bilingual lexicon. During reading, these words produce the cognate facilitation and the homograph interference effects. For example, bilinguals read cognates (e.g., Dutch-English: *sport-sport*; Dutch-German: *dier-Tier*) faster, than control words (Dijkstra et al., 1999). In contrast, they recognize homographs (e.g., German-English: *tag (day)-tag*) slower than control words (Von Studnitz & Green, 2002). These effects are explained by the notion that bilinguals simultaneously activate orthographic, phonological and semantic representations in both languages during reading (Assche et al., 2009). For cognates, the three codes have high similarity across languages, and this similarity helps to accelerate cross-linguistic activation of cognates relative to control words. For homographs, there is considerable semantic interference, which slows down responding.

In Experiment 3, I compared VWFA activity for cognate and homograph primetarget pairs in a group of fluent Spanish-English speakers. Both cognates and homographs share visual word forms across languages, but only cognates also share their meaning. The orthographic similarity between these lexical items can be used to measure transient neural adaptation in the VWFA following presentation of such words in one and then the other language. Using both cognates and homographs during this procedure can help in determining whether semantic information plays a role in activating the VWFA. If the VWFA is functionally specialized for processing visual word forms, then neural activity in this area would not be expected to change as a function of semantic overlap across two languages (i.e, as in the case of cognates). However, if the function of the VWFA is to integrate visual orthographic representations with word meaning, then activity in the VWFA will be modulated by semantic similarity.

VWFA and the reading network

Although the identification of brain regions that are activated during reading provides some understanding of how words are processed, a thorough account of reading will involve understanding of how those regions interact. Two forms of connectivity analyses can be used to study the interactions among brain areas. One type, functional connectivity analysis, finds connections between spatially distinct regions of the brain by looking at how neural activity in these regions is correlated in time. Using this approach, Mechelli et al. (2005) found that activity in the left posterior fusiform gyrus (and parts of the VWFA) was tightly coupled with activity in the inferior frontal gyrus and superior temporal gyrus. But functional connectivity analyses cannot reveal the mediators of such correlations; they cannot differentiate between a stimulus-locked response produced by a common afferent (feed-forward) input and the stimulus-induced oscillations mediated by synaptic connections (Friston & Büchel, 2003). An alternative approach, effective connectivity analysis, measures the influence that one neural region exerts on another and, consequently, can uncover the underlying causal structure of network activity. However, common effective connectivity algorithms are not without flaws themselves. Dynamic causal modeling algorithm (DCM), for example, tests a hypothetical model with pre-defined directed connections between brain areas against the actual brain activation (Friston, 2003; Schuyler et al., 2010). But the number of alternative possible causal structures for a set of 10 ROIs (Regions of Interest) could be on the order of

billions (Ramsey et al., 2010). Thus, while the DCM tests *a model* of brain interactions, it does not generate the best possible model. Another serious problem of some effective connectivity algorithms, such as structural equation modeling (McIntosh and Gonzalez-Lima, 1994), is that they are fitted to the measured timeseries of activation. The measured hemodynamic response provides only an indirect estimate of the underlying neural response (Stephan et al., 2006). Such indirect measurement coupled with potentially incomplete knowledge about all mediating ROIs within a given network may lead to the discovery of false causal connections (Ramsey et al., 2010). A related challenge for algorithms that rely on timeseries information is the inherent bias that results from variability in the BOLD delays across different brain regions. These differences in the latency of hemodynamic response may lead to false inferences about connectivity (Stephan et al., 2006).

Graphical Modeling with IMaGES

Prompted by these challenges to modeling of causal connections among brain regions, Ramsey and colleagues developed a Bayesian search algorithm called IMaGES (Independent Multiple sample Greedy Equivalence Search, Scheines et al., 1998; Ramsey et al., 2010; Ramsey, Hanson, Glymour, 2011).

IMaGES was designed to extract feed-forward causal structure from fMRI timeseries by exploring the possible decision space and constraining the search to connections that carry the greatest predictive power (Perez, El-Sheikh, & Glymour, 2010). The algorithm starts with an empty graph for a set of ROIs. It then selects all possible



Figure 4.1: Pre-processing of BOLD time series for analysis with IMaGES BOLD time series are first extracted from regions in the brain; simultaneous regional activity is explored by analyzing over time windows with varying lags. Residuals from pairwise lag regressions are fed in parallel into IMaGES (Figure provided courtesy of Dr. Stephen José Hanson).

models with one directed link and rates the models based on residuals computed in each time-series dataset. The model with the highest average Bayesian Information Criterion (BIC) score is selected. Next, models with two links are considered. At each stage, the algorithm attempts to maximize the BIC score. When additional links no longer improve the BIC score, a backward procedure is initiated. The backward procedure removes links using an analogous method (Ramsey, Hanson, & Glymour, 2011).

IMaGES offers an exploratory approach in that it discovers the underlying causal structure instead of testing a pre-determined hypothetical model, as is the case with many other effective connectivity algorithms (Figures 4.1 & 4.2 for details of the analysis).



Figure 4.2: Graphical search procedure in IMaGES

Individual sets of residuals are simultaneously submitted to the algorithm, which begins the search optimized by the goodness of fit (GOF) constraints. It produces a final graph common for all individuals in the data set (Figure provided courtesy of Dr. Stephen José Hanson).

It exploits the strength of association between variables and cross-subject redundancy to eliminate spurious connections that result from indirect measurement of brain activity. IMaGES produces reliable and stable estimates of interactions between different ROIs. It was recently validated on 28 Smith et al. (2011) benchmark simulations where it
performed at above 90% on precision of detecting connections and on recall of orientations (Ramsey, Hanson, & Glymour, 2011).

In Experiment 3 IMaGES was used to describe the interactions between the VWFA and other brain areas, previously implicated in language processing. The algorithm used BOLD timeseries from VWFA and other theoretically defined ROIs. These ROIs included the left posterior middle temporal gyrus (MTG; implicated in processing of single word meaning, Hickok & Poeppel, 2004; Jobard et al., 2003); left Heschl's gyrus (HG; thought to store acoustic-phonemic speech codes, Hickok & Poeppel, 2004); left angular gyrus (AG; linked with grapheme-to-phoneme rule system, Hillis et al., 2005; Temple et al., 2001), left opercular inferior frontal gyrus (IFG; involved in articulatory speech coding, as well as, semantico-syntactic processing; e.g., Hickok & Poeppel, 2004; Jobard et al., 2003; Klein et al., 2006) and left temporal pole (TP; involved in simple combinatory semantics; e.g. Abel et al., 2009). The right homologue of the VWFA was also used because it was found to be active during reading in bilingual speakers (e.g., Nelson et al., 2009; Perfetti et al., 2007).

In this experiment I combined evidence from localization methods, expected to reveal quantitative differences in brain activation, such as a difference in the amount of neural activity across conditions, with evidence from effective connectivity analysis, expected to reveal qualitative differences, such as variations in the pattern of interactions between brain areas. If reading cognates and homographs leads to qualitative differences in brain activation, then causal connections between the VWFA, thought to support early stages of reading, and other ROIs should differ for these two types of stimuli. Consistently with models of language processing in monolinguals (e.g., Coltheart et al., 1993; Dell, 1986, McClelland & Rumelhart, 1981) and bilinguals (e.g., Dijkstra& van Hell, 2002; Kroll & Stewart, 1994), and with neural models of language comprehension (e.g., Hickok & Poeppel, 2004) I expected to uncover causal connections between areas processing orthographic features and areas processing semantics with projections to areas involved in preparation of motor codes for speech production. In addition, feedback connections were expected from areas processing semantics to posterior temporal regions and the VWFA, in line with more recent findings of early semantic contribution to reading (e.g., Cornelissen et al., 2009; Devlin et al., 2006).

Of additional interest was whether the connectivity among ROIs differed when reading in first and second language. Although it is possible that the VWFA segregates languages by relying on the neural activity across voxels that were uniquely activated by each language (see Experiments 1 and 2), additional segregation of languages may be necessary due to orthographic discrepancies between English and Spanish, such as syllable complexity and consistency of spelling-to-sound mapping. These discrepancies may require that different neural networks become engaged during reading. There is some evidence of this in recent neuroimaging literature (e.g., Bick, Goelman, & Frost, 2011; Das, Padakannaya, Pugh, & Singh, 2011; Jamal et al., 2011; Paulesu et al., 2000). Languages with transparent orthographies, like Spanish, Italian, Hindi, and Russian, may rely more on the sub-lexical processes, localized to dorsal brain areas (e.g. AG and SMG); whereas languages with less transparent orthographies, like English and French, may preferentially recruit the lexical processes, localized to ventral brain areas (e.g., MTG, TP) [see Coltheart et al. (1993) for a psycholinguistic model of these processes]. A combination of localization methods with effective connectivity analyses is better suited to uncover such processing differences than spatial localization alone.

Experiment 3 pursued two main goals. The first goal was to determine the role of the VWFA in reading by assessing the degree of its sensitivity to semantic similarity between word forms in two languages. And the second goal was to ground the understanding of the neural processes in the VWFA in the context of its interactions with other parts of the reading network. To address the second goal, I used a new modeling approach, which revealed causal feed-forward connections between the VWFA and other parts of the reading network.

Method

Participants

The participants recruited for Experiment 1 also participated in Experiment 3.

Materials

To evaluate the VWFA response to Spanish and English words that vary in their semantic and orthographic similarity 120 pairs of Spanish and English words were selected as stimuli. The words in each pair were either cognates (30 pairs), with matching orthography and meaning (e.g., part*-parte*); homographs (30 pairs), with matching orthography, but different meaning (e.g., pie-*pie* (foot)); translation equivalents (30 pairs), with different orthography, but matching meaning (e.g., steel-*acero*); or unrelated words (30 pairs), with different orthography and meaning (e.g., movie-*barco* (boat)). In addition, I selected 15 pairs of unrelated English words (e.g., tie-jet), 15 pairs of unrelated Spanish words (e.g., *rama* (branch)-*tela* (cloth)), 15 pairs of repeating

English words (e.g., belt-belt) and 15 pairs of repeating Spanish words (e.g., *cadena-cadena* (chain)). This resulted in 180 stimulus pairs. In each pair, one stimulus was designated as the prime and the other as the target. For half of the stimulus pairs, the target was in Spanish and for the other half the target was in English. For each pair, words were matched on frequency in written text and length and all sets (cognates, homographs, translations, unrelated, repeated) were matched on average frequency and length (Kucera & Francis, 1967; Davies, 2002). Frequency and length measures for the stimuli are provided in Table 4.1. In addition to the word stimuli, 90 readable non-words and 90 consonant strings were created for use in a word/non-word decision task. The non-words were created by changing 2-3 letters in real English and Spanish words of similar frequency as the 180 word pairs. The consonant strings were created by randomly selecting consonants and constructing strings of similar length as the 180 word pairs.

	Frec	luency	Le	ngth
Pair Type	M	SD	M	SD
Cognates				
English word	40.5	35.17	5.06	.83
Spanish word	37.35	36.43	5.3	1.06
Homographs				
English word	40.43	62.13	5.17	1.60
Spanish word	40.68	49.80	5.23	1.59
Translations				
English word	40.73	25.90	5.57	1.25
Spanish word	31.66	27.26	5.63	1.25
Unrelated				
English word	34.97	16.94	5.17	1.29
Spanish word	37.15	23.35	5.4	1.22
Spanish Unrelated				
Spanish word	37.25	46.27	5.73	1.22

Table 4.1: Average frequency and length measures and their standard deviations for English and Spanish prime-target word pairs.

Spanish word	37.55	46.19	5.93	1.10	
English Unrelated					
English word	38.53	17.98	5	1.46	
English word	39.73	17.26	4.93	1.49	
Spanish Repeat					
Spanish word	37.77	21.46	5.4	1.06	
English Repeat					
English word	38.53	13.99	5.47	1.30	

Note. Frequency measures for English were obtained from Kucera & Francis (1967). Frequency measures for Spanish were obtained from Davies (2002). Frequency measures represent instances per million and length measures represent number of letters.

Procedure

Participants were presented with a series of letter strings and asked to decide for each letter string whether it was a word or a non-word. The stimuli were back-projected onto a transparent screen and reflected in the mirror attached to a head coil. Responses were made by pressing one of two buttons on a response box. Participants were told that they should try to answer as quickly and as accurately as possible. Early activation of the VWFA was examined by using a masked priming paradigm, in which a prime is presented briefly and is forward-masked by random symbols and backward-masked by the onset of the target, such that the subject is aware of the target only. This paradigm is used to capture early differences in neural activity, rather than the reverberation of information through neuronal feedback loops (Del Cul, Baillet, & Dehaene, 2007). Each trial began with a fixation screen presented for 3.5 s and jittered by an average of 2 s. A forward mask consisting of random symbols was presented for 440 ms followed by a prime word in lowercase letters for 60 ms. A target word was presented in capital letters and remained on the screen until participants responded or until 3 s had elapsed (see Figure 4.3). The order of stimulus presentation was randomized. There were 2 runs and

each run consisted of 90 trials in English and 90 trials in Spanish, for a total of 360 trials. During English trials, participants responded to English targets preceded by Spanish primes. During Spanish trials, participants saw Spanish targets preceded by English primes. In addition, on 15 of the English trials participants were presented with repeating English prime-target pairs (*belt-belt*) and on another 15 trials they were shown unrelated English prime-target pairs (*tie-jet*). Similarly, 15 of the Spanish trials consisted of repeating Spanish prime-target pairs (*cadena-cadena*) and another 15 were unrelated Spanish prime-target pairs (*rama-tela*). Whether English or Spanish trials were presented first was randomized. Participants were queued at the start of each language phase. In half of all trials the targets were real words, and required a 'word' response, the other half of the trials consisted of non-words and consonant strings, and required a 'non-word' response. Participants' reaction times and accuracy during the word/non-word decision period, as well as their blood-oxygen level dependent brain activity were recorded.

fMR Image Acquisition

The same data acquisition protocol was used as in Experiment 1. The data were acquired on the same day. The data for Experiment 3 were acquired after data acquisition for Experiment 1.

fMRI Localization Analysis

The same initial image preprocessing and data analysis steps were taken as in Experiment 1. Upon completing data preparation, I used a three-level statistical analysis approach to measure the neural response across different conditions. Condition effects were first estimated in individual participants using FEAT (FMRI Expert Analysis Tool) first-level analysis. Individual participant *z* (Gaussianised *t/F*) statistic images were contrasted with a fixation baseline and thresholded using clusters determined by *z*>1.96 and a (corrected) cluster significance threshold of *p*=.05. The results from two runs for each participant were combined using a fixed-effects model. These results were then entered into a group-level analysis, where condition differences were estimated by comparing each experimental condition to an unrelated prime-target control condition. The higher-level analysis was carried out using FLAME 1+2 mixed-effects analysis (Beckman, Jenkinson, & Smith, 2003). Group-level *z* (Gaussianised *t/F*) statistic images were thresholded using clusters determined by *z*>1.96 and a (corrected) cluster significance threshold of *p*=.05 (Worsley, 2001).



Figure 4.3: Cross-language priming task.

Subliminal prime activates the form and meaning representations in English and Spanish. It is masked by the capitalized target, which prevents its further processing. Consequently, only the early effects due to activation of the prime are measured.

IMaGES Graphical Analysis

The same pre-processing was applied to the functional BOLD timeseries as in the localization analysis. The reading ROIs were defined for each participant using the Harvard-Oxford Cortical Atlas available through FSL 4.1 software (FMIRB's Software Library, http://www.fmrib.ox.ac.uk/fsl/). We defined ROIs theoretically in order to ensure that the size of each ROI did not differ across participants and that the same ROIs were evaluated across multiple conditions. Mean voxel timeseries in a given ROI were extracted using Featquery (FMIRB's Software Library, http://www.fmrib.ox.ac.uk/fsl/; Mumford, 2007). Numeric activation values for 7 ROIs and 11 participants were entered into the IMaGES algorithm (Scheines et al., 1988). Separate graphical analyses were performed for each prime-target pair type (cognates, homographs) and for each priming direction (Spanish-English, English-Spanish). IMaGES produced a Markov equivalence class of models for each analysis. A Markov equivalence class contains models with the same adjacencies, but different direction of connections (Ramsey et al., 2010). By introducing an additional a priori constraint that the left VWFA should project feedforward connections, rather than receive them, I were able to find a single best fitting model per condition. Model fit was estimated using SEM parametric model with a regression optimizer. The overall model significance was determined using a chi-square test.

Results

Reaction Time

Reaction time data were analyzed separately for English and Spanish trials. For English, a 2x8 repeated-measures ANOVA with run (first, second) and prime-target pair type (cognates, translations, homographs, unrelated, repeated, within-language unrelated, consonants, non-words) as within-subjects variables showed a main effect of prime-target pair type ($F_1(7,42) = 19.28$, p < .001, partial $\eta^2 = .66$; item analysis: $F_2(7, 164) = 78.76$, p < .001, partial $\eta^2 = .77$). No main effect of run and no significant interaction of run and prime-target pair type were found in neither the subject, nor the item analysis. For all subsequent analyses, reaction times were averaged across two runs. The main effect of prime-target pair type was followed up with planned comparisons. There was a marginal advantage for recognition of cognate targets (M = 724.54 ms, SE = 37.71 ms) over unrelated English targets (M = 769.23 ms, SE = 46.08 ms) in the subject, but not the item analysis, $t_1(11) = 1.87$, p = .088. In addition, participants recognized non-words more slowly than all other stimuli (all p's < .005).

For Spanish, a 2x8 repeated-measures ANOVA with run and prime-target pair type as within-subjects variables showed a main effect of prime-target pair type ($F_1(7,42)$ = 9.86, p<.001, partial η^2 =.62; $F_2(7, 164)$ = 49.99, p < .001, partial η^2 =.68). As no main effect of run and no significant interaction of run with prime-target pair type were found in neither the subject, nor the item analysis, reaction times were averaged across two runs. The main effect of prime-target pair type was investigated with planed comparisons. Relative to the cross-language unrelated control condition, significantly slower reaction time was found for homographs ($t_1(10) = -2.81, p < .05; t_2(28) = 1.76, p = .09$) and for the within-language unrelated control condition ($t_1(10) = -3.88, p < .005; t_2(28) = 2.20, p < .05$). See Table 4.2 for mean reaction times per condition. Relative to the within-language unrelated control condition time advantage was found for repeated prime-target pairs ($t_1(10) = 3.81, p < .005; t_2(28) = 3.37, p < .005$), cognates (t_1 $(10) = 5.80, p < .001; t_2 (28) = 2.87, p < .01)$, and translations $(t_1 (10) = 4.29, p < .005; t_2 (28) = 2.62, p < .05)$. In addition, relative to homographs faster reaction times were found for repeated prime-target pairs $(t_1 (10) = 3.12, p < .05; t_2 (28) = 2.87, p < .01)$, cognates $(t_1 (10) = 3.49, p < .01; t_2 (28) = 2.28, p < .05)$, and translations $(t_1 (10) = 3.86, p < .005; t_2 (28) = 2.62, p < .05)$. The word stimuli and consonant strings were recognized faster than the non-word stimuli (all *p*'s < .005).

	Mean Reaction	Standard Error	Mean Accuracy	Standard
Prime-Target Pair Type	Time (ms)	(ms)	(proportion correct)	Error
Spanish Phase				
Repeated	772.89	46.10	.97	.01
Cognates	788.32	60.36	.96	.02
Translations	812.73	51.03	1.00	.00
Homographs	1030.62	98.21	.89	.03
Cross-Language				
Unrelated	832.66	54.77	.99	.02
Within-Language				
Unrelated	1028.37	83.10	.91	.03
Consonants	696.15	26.04	.99	.01
Non-Words	1450.44	156.31	.62	.10
English Phase				
Repeated	738.59	41.39	.99	.01
Cognates	728.49	41.09	.99	.01
Translations	715.16	29.47	.99	.01
Homographs	731.43	35.03	.99	.01
Cross-Language				
Unrelated	719.20	32.36	.98	.01
Within-Language				
Unrelated	764.51	50.21	1.00	.00
Consonants	705.27	26.06	.99	.01
Non-Words	1186.77	120.91	.84	.06

Table 4.2: Reaction time and accuracy results during word/non-word decision task in Spanish and English broken down by the type of prime-target relationship.

<u>Accuracy</u>

Accuracy data were analyzed separately for English and Spanish. The data are provided as proportion correct. For English, a 2x8 repeated-measures ANOVA with run and prime-target pair type as within-subjects variables showed a main effect of primetarget pair type ($F_1(7,42) = 7.62$, p < .001, partial $\eta^2 = .56$; $F_2(7, 164) = 25.73$, p < .001, partial $\eta^2 = .52$) and a significant interaction between prime-target pair type and run (F_1 (7,42) = 2.67, p < .05, partial $\eta^2 = .31$; $F_2(7, 164) = 3.88$, p < .005, partial $\eta^2 = .14$). The interaction was investigated further with a series of paired-samples t-tests, which showed that non-words were identified with lower accuracy during the first run. This effect was significant only in the item analysis ($t_2(43) = -3.34$, p < .005) and showed a nonsignificant trend in the subject analysis. No other differences were observed. Therefore, accuracy data were averaged across runs. Subsequent analyses showed that non-words (M=.86, SE=.05) were identified with less accuracy than all other stimuli (all p's < .05).

For Spanish, a 2x8 repeated-measures ANOVA with run and prime-target pair type as within-subjects variables showed a main effect of prime-target pair type (F_1 (7,42) = 17.65, p < .001, partial $\eta^2 = .75$; F_2 (7, 164) =73.26, p < .001, partial $\eta^2 = .76$) and a significant interaction between prime-target pair type and run (F_1 (7,42) = 3.30, p < .01, partial $\eta^2 = .36$; F_2 (7, 164) =2.20, p < .05, partial $\eta^2 = .09$). The interaction was investigated with a series of paired-samples t-tests, which showed that consonant-strings were identified less accurately during the first run (M=.96, SE=.02) than during the second run (M=1, SE=0), t_1 (6) = -2.60, p < .05; t_2 (43) = -3.03, p < .005. In addition, in the item-analysis, significantly lower accuracy was found for non-words during the first run (M= .51, SE = .03) compared to non-words during the second run (M= .63, SE = .04), $t_2(43) = -2.55$, p < .05. As consonant-strings and non-words were not part of planned comparisons, accuracy data were averaged across runs for further analyses. Relative to the cross-language unrelated control condition, homographs were identified less accurately, $t_1(10) = -3.31$, p < .01; $t_2(28) = -2.38$, p < .05 (See Table 4.2). Relative to the within-language unrelated control condition, greater accuracy was found for translations, $t_1(10) = 2.76$, p < .05; $t_2(28) = 2.47$, p < .05. In addition, relative to homographs, significantly greater accuracy was found for repeated prime-target pairs ($t_1(10) = 2.25$, p < .05; $t_2(28) = 1.99$, p = .057) and translations ($t_1(10) = 3.68$, p < .005; t_2 (28) = 2.84, p < .01), and a marginal advantage was found for cognates ($t_1(10) = 1.98$, p = .075; $t_2(28) = 1.56$, p = .13). The word stimuli and consonant strings were recognized more accurately than the non-word stimuli (all p's < .005).

Activation Maps

During a word/non-word decision task in Spanish, homograph pairs produced a deactivation in several brain areas when compared to the unrelated prime-target pairs. These brain areas included the VWFA; temporo-occipital parts of the left inferior temporal and middle temporal gyri (MTG), left angular gyrus (AG), left thalamus, bilateral superior and inferior lateral occipital cortex, precuneus, posterior part of cingulate gyrus and left cerebellum (see Table 4.3 and Figure 4.4). Timeseries of activation extracted from the VWFA cluster (with peak coordinates z = -50, y = -48, z = -26, Z = 2.48) showed that model parameter estimates for homographs in this cluster were significantly lower than parameter estimates for the unrelated pairs (t (10) = 2.31, p<.05). Similarly, timeseries of activation extracted from two other regions deactivated in the homograph condition: the temporooccipital part of the left MTG and the posterior part of

the left AG showed lower mean parameter estimates for homographs relative to the unrelated pairs condition (left MTG: t(10) = 2.50, p < .05; left AG: t(10) = 2.31, p < .05; see Figure 4.5). The same was not observed for either the cognate or the translation prime-target pairs. In fact, cognate prime-target pairs did not differ significantly from either the homograph or the unrelated pairs.

Table 4.3: Local maxima of neural activation during primed word recognition in English and Spanish. Conditions are labeled first with the language of the prime and then the language of the target. Each activation peak is described by a *z*-statistic, related to the intensity of activation and x, y, z coordinates in standard Montreal Neurological Institute (MNI) brain space.

Harvard-Oxford Cortical Structural Atlas Label	<i>z</i> - statistic	x	у	Z
English-Spanish Homographs < English-Spanish Unrelated				
Left Middle Temporal gyrus, temporooccipital part	2.51	-60	-56	4
Left Angular Gyrus	2.37	-60	-56	12
Left Angular gyrus/Supramarginal gyrus	2.33	-60	-54	14
Left Middle Temporal Gyrus, temporooccipital part	2.43	-56	-50	-6
Left Inferior Temporal gyrus, temporooccipital part	2.47	-50	-48	-26
Left Lateral Occipital cortex, superior	2.81	-44	-74	26
Left Lateral Occipital cortex, superior	2.93	-14	-74	48
Left Precuneus	2.53	-14	-56	14
Left Thalamus	2.41	-12	-32	4
Left Lateral Occipital cortex, superior	2.68	-10	-68	56
Cingulate gyrus, posterior	2.62	-10	-34	32
Right Precuneus	2.66	2	-44	44
Right Lateral Occipital cortex, superior	2.62	22	-78	44
Spanish Repeated > Spanish-Spanish Unrelated				
Left Planum Temporale/Heschl's gyrus	2.44	-58	-16	6
Left Lateral Occipital cortex, inferior	2.49	-56	-64	-4
Left Inferior Temporal gyrus, temporooccipital part	2.66	-52	-48	-14

	Left Middle Temporal gyrus, posterior	2.86	-52	-16	-10
	Left Inferior Temporal gyrus, temporooccipital part	2.38	-46	-52	-22
	Left Angular gyrus/Supramarginal gyrus	2.42	-44	-54	48
	Left Temporal Occipital Fusiform cortex	2.62	-42	-62	-16
	Left Angular Gyrus	2.71	-36	-58	30
	Left Superior Parietal lobule	2.52	-36	-52	48
	Left Lateral Occipital cortex, superior	2.36	-30	-74	34
	Left Precentral gyrus	2.59	-30	-22	50
	Left Lateral Occipital cortex, superior	2.26	-28	-66	48
Spanish-English Translations < Spanish-English Unrelated					
	Left Occipital Fusiform gyrus	2.63	-40	-68	-24
	Left Temporal Occipital Fusiform cortex	2.47	-24	-60	-20
	Left Parahippocampal gyrus, posterior	2.59	-18	-38	-6
	Left Lingual gyrus	2.42	-14	-74	-16
	Cerebellum, posterior lobe	2.42	0	-64	-12
	Right Lingual gyrus	2.48	4	-62	2

Note. Group-level Z (Gaussianised t/F) statistic images were thresholded using clusters determined by Z>1.96 and a (corrected) cluster significance threshold of p=.05.

Repeated Spanish prime-target pairs produced activations in the left angular gyrus, temporooccipital part of the left inferior temporal gyrus, posterior part of the middle temporal gyrus, left superior parietal lobule, left precentral gyrus and the VWFA relative to the unrelated Spanish prime-target pairs (see Table 4.3). This was in contrast to the repeated English prime-target pairs as no activation was observed for these stimuli relative to the unrelated English baseline. To illustrate these effects, timeseries of activation were extracted from three of the deactivated regions (VWFA, left MTG, and left AG). This showed significantly higher parameter estimates for the Spanish repeated condition in the VWFA (t(10)=2.63, p<.05), the left MTG (t(10)=2.67, p<.05) and the left

AG (t(10)=2.62, p<.05) and no differences relative to baseline for the English repeated condition (see Figure 4.6).



Figure 4.4: Areas of priming-related suppression and enhancement relative to the baseline condition. Group-level *z* (Gaussianised *t/F*) statistic images were thresholded using clusters determined by *z*>1.96 and a (corrected) cluster significance threshold of *p* =.05. Brain slices were selected based on a peak voxels closest to the canonical location of the VWFA (x= -44, y = -58, z = -15; Jobard et al., 2003). Images are presented following the radiological convention. Areas of activation are shown in red, deactivations are shown in blue.





Neural activity in each condition was compared to the cross-language unrelated prime-target baseline. Here and in all subsequent figures * p < .05.





Neural activity in each condition was compared to the within-language unrelated prime-target baseline.

During a word/non-word decision task in English, translation prime-target pairs produced deactivation in bilateral parahippocampal gyrus and hippocampi, bilateral lingual gyrus, left cerebellum and left temporal occipital fusiform gyrus with peak deactivation medial to the VWFA (see Table 4.3). Timeseries of activation extracted from the left hippocampus cluster (with peak coordinates x=-18, y=-38, z=-6, Z=2.59) showed significantly lower model parameter estimates for translations relative to unrelated pairs (t(10)=2.60, p<.05). Similarly, timeseries of activation extracted from the right hippocampus cluster (with peak coordinates x=30, y =-38, z=-8) showed significantly lower parameter estimates for translations relative to unrelated pairs (t(10)=2.51, p<.05). No such deactivation was observed for cognates or homographs (see Figure 4.7).





Neural activity in each condition was compared to the cross-language unrelated prime-target baseline.

IMaGES Graphs

The model statistics for each IMaGES graph and averaged regression coefficients for each connection are provided in Table 4.4. All chi-square tests, conducted following the assumptions outlined in the algorithm (Scheines et al., 1988), were significant. The graphical models obtained during this analysis showed that after visual input reached the VWFA, it was transferred to the temporal pole, the middle temporal gyrus, and finally to the inferior frontal gyrus along one of two routes: via a direct/ventral connection from the middle temporal gyrus in the temporal lobe, or via an indirect/dorsal link through the angular gyrus in the parietal lobe (See Figure 4.8). When participants were shown English targets, a direct connection to the inferior frontal gyrus was observed, and when they were shown Spanish targets, the inferior frontal gyrus was accessed via the angular gyrus.

No differences were found across conditions for the connections from the VWFA. The VWFA always projected to the TP and the right VWFA. However, I found a difference between connections of an area adjacent to the VWFA, the left posterior MTG. This region seemed to mediate projections to the IFG, the AG, or both, in all but one case, and this was when participants read homographs in Spanish. This finding is discussed in the next section.

I able 4.4: Model statistics for IMaGES graphs	•
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4 4 3 4

IMaGES graph	Total BIC Score	Degrees of Freedom	Chi-Square	<i>p</i> -value
English - Spanish Cognates	34.2036	15	75.7924	0.000
Spanish - English Cognates	11.6667	15	52.2875	0.000

English-Spanish Homographs	5.2787	15	35.3421	0.002
Spanish-English Homographs	5.4592	15	35.1616	0.002

Note: Model statistics were computed in the IMaGES algorithm using the model explained in Bollen "Structural Equations with Latent variable" (p.110).



Figure 4.8: Analyses of effective connectivity between areas implicated in language processing.
Results are broken down by prime-target pair type (cognates vs. homographs) and by language of the target (English vs. Spanish). The numbers represent group regression coefficients and mean Bayesian Information Criterion (BIC) scores. Regions of interest were defined theoretically using the Harvard-Oxford Cortical Atlas. TOFC - Temporal Occipital Fusiform cortex; MTG - Middle Temporal Gyrus; AG
Angular gyrus; HG - Heschl's gyrus; TP - Temporal pole; IFG - Inferior Frontal gyrus.

Discussion

Reaction Time and Accuracy

The behavioral results for this group of participants were consistent with previous research on single-word reading in bilinguals showing cross-linguistic influences, across many different tasks, including word reading and primed lexical decision (e.g., Dijkstra, Grainger, & Van Heuven, 1999; Duyck, 2005; Jared & Kroll, 2001; Van Heuven, Dijkstra, & Grainger, 1998). In Experiment 3, participants recognized English words faster when they were primed with Spanish cognates than when they were primed with unrelated Spanish words. They also recognized Spanish words faster when they were primed with English cognates or identical Spanish words, than when they were primed with unrelated Spanish words. Similarly, they recognized Spanish words faster and more accurately when they were primed with English translations, than when they were primed with unrelated Spanish words. In addition, participants recognized Spanish words more slowly and less accurately, when they were primed with English homographs, compared to unrelated English words.

These results indicate that primes in one language that share both orthographic and semantic similarity with targets in another language will facilitate word recognition. However, when primes in one language share orthographic, but not semantic similarity with the targets, word recognition will be hindered in bilinguals. As suggested by Dijkstra and van Heuven (2002), any facilitation produced by overlapping word forms is eliminated by competing semantics. In fact, the semantic competition for homographs is stronger than for two unrelated words, possibly due to the early orthographic facilitation. Presentation of two highly similar orthographic forms leads to a strong activation of two distinct word meanings, which subsequently compete for selection. In contrast to homographs, cognates activate the same, or highly overlapping, orthographic and semantic representations. Moreover, cognates may also have strong feedback connections from semantics to orthography, which speeds up lexical access even more (Reimer, Brown, & Lorsbach, 2001 as cited in Dijkstra & van Heuven, 2002). These behavioral results are consistent with a model of the bilingual lexical access, where the presentation of written words simultaneously activates orthographic candidates in both languages. The activated orthographic representations then link with the corresponding semantic (and phonological) representations and this is followed by a competition between the potential lexical candidates. The candidate with the highest level of activation wins the race for lexical selection.

Interestingly, Experiment 3 also revealed stronger priming effects from English to Spanish, than from Spanish to English. This effect replicates previous word-recognition studies in which greater cross-linguistic influence was shown for one language of a bilingual (e.g., Dijkstra & Van Heuven, 2002; Duyck, 2005). This effect may be explained by the fact that proficiency is usually greater in one language (or by differences in age of acquisition and history of language use; e.g., Zevin & Seidenberg, 2002; Jared & Kroll, 2001; Gerard & Scarborough, 1989; Grosjean, 1997). For example, monolingual interlocutors and language settings influence a bilingual's language choice by increasing the use of one language and decreasing its threshold of activation. As a result, the language used more frequently long-term may become dominant and more readily available for processing, and this variability in individual history of language use may contribute to bilinguals' asymmetry in word recognition across languages. For the group of bilinguals who participated in Experiment 3, average reaction time was 100 to 200 ms slower in Spanish than in English (see Table 4.2), and their accuracy at detecting false words was lower for Spanish than for English, suggesting that these bilinguals processed words more efficiently in English. Many studies in the behavioral literature on bilingualism document a similar asymmetry, where the bilingual's dominant, or the more proficient, language reliably affects processing in the non-dominant, or less proficient, language; whereas the reverse is not generally found (e.g., Chen, Cheung, & Lau, 1997; Silverberg and Samuel, 2004; Van Hell and Dijkstra, 2002; Weber & Cutler, 2004). This behavioral result can also be interpreted in light of our effective connectivity results, which illustrate a striking difference in neural mechanisms underlying English and Spanish target reading. We will return to this point later in the discussion.

The behavioral results in Experiment 3 fit well within the framework of the Bilingual Interactive Activation model (BIA+, Dijkstra and van Heuven, 2002), which suggests that the more proficient and the less proficient languages may differ with respect to the resting level activation of words in these languages. Words in a more proficient language are likely to be used more frequently and therefore may acquire a larger resting activation relative to words in the other language. Consequently, words in the less proficient language are delayed in terms of their semantic and phonological coding from orthography. This effect is called the *temporal delay assumption* (e.g., van Heuven & Dijkstra, 2010). A result of such delay in activating lexical representations is that crosslinguistic effects are generally larger from the more proficient language into the less proficient language, than the reverse.

The dynamic nature of bilingual lexical representations is also captured in Kroll and Stewart's (1994) Revised Hierarchical Model (RHM). According to the RHM, bilinguals' proficiency influences first and second language processing and underlying representational mechanisms. During initial stages of second language acquisition, second language (L2) words are connected to first language (L1) words via lexical links, and L1 words are in turn connected to semantic information. As bilinguals continue to learn the second language and their proficiency level increases, L2 words begin to form direct links to conceptual representations. At later stages of acquisition, L2 words have established connections with conceptual information, but the links between L2 and L1 at the lexical level are preserved and may be relied upon when processing in a highlyproficient second language. The RHM proposes that the strength of various connections is not the same, with conceptual representations linked more strongly to L1 lexical representations than to L2 lexical representation. At the lexical level, the path from L2 to L1 is stronger than the path from L1 to L2. Connections of different strength suggest an asymmetry in bilingual lexical organization and processing. For example, semantic information may become activated earlier for words in L1 than for words in L2, and this, in turn, creates greater priming effects when L1 cognates and translations precede their L2 counterparts.

Of the two models, the BIA+ seems to be more consistent with the results obtained so far. BIA+ assumes that the bilingual lexica are integrated at all levels of processing: orthographic, phonological and semantic. The RHM, on the other hand, proposes fully separate orthographic repositories for L1 and L2 orthographies. The RHM model, therefore, may be more suitable for languages that use different writing systems (like English and Chinese). In contrast, the results of Experiment 1 and 2 showed that the assumption of separate orthographic lexica is incorrect for languages like English and Spanish. I have shown that these two languages rely on processing by overlapping neural populations. However, in a 2010 revision of the RHM Kroll and colleagues argued that structural overlap does not necessarily rule out functional separation. They suggested that one way the brain could functionally separate orthographies is by using different levels of activation across the same neural tissues. The results of Experiment 2 address this hypothesis. Unlike GLM, multivariate pattern analysis techniques consider patterns of covariation across brain voxels. As such, they utilize both maximal sub-maximal activity levels across brain voxels. Using MVPA, I showed that voxels in the VWFA, a neural correlate of the orthographic input lexicon, are co-activated for words in different languages. Even if language tagging is performed by the non-overlapping voxels, these results suggest that, with the exception of a potential language flag, orthographic processing in English and Spanish relies on the same neural mechanisms. Of course, these findings do not rule out the existence of language-specific responses at the neuronal level. For example, co-activated and overlapping cortical areas for first and second language could still represent the firing of different neurons located in close proximity to one another. To date limited evidence is available regarding the individual neuron responses to written words and therefore, it may not be possible to completely discard this possibility. The data on local field potentials from intracranial recordings are relevant to this argument. These data are collected form preoperative patients with medically intractable epilepsy, usually near the sites of origin of the epileptic seizures (e.g., Schwartz et al., 1996; Ojemann et al., 1988). As such, they are limited in both the location of the recordings and in the power to generalize to normal healthy brains. However, despite these caveats, these data are informative with respect to general characteristics of stimulus-locked neuronal firing in humans. Ordinarily, such recordings

find relatively specialized responses to various language processes, such as object naming and word reading, even at recording sites located in adjacent parts of cortex (Schwartz et al., 1996). Whether we can assume similar neuronal tuning profiles in other parts of cortex remains an open question until more complete datasets become available.

Another plausible means of segregating function given structural overlap is via imposing different connectivity patterns for first and second language. The results of the graphical effective connectivity analysis are relevant here and I will return to the discussion of the models of bilingual language processing in the section on IMaGES analysis.

Activation Maps

Neuroimaging results showed that presentation of Spanish words, primed with English homographs, produced a decrease in the VWFA activity relative to the control condition. This finding could be explained by neural adaptation (Grill-Spector & Malach, 2001; Henson, 2003) of the VWFA following presentation of two words that are similar in orthography. Neural adaptation effects in the VWFA are well documented for monolingual participants (e.g., Devlin et al., 2006; Glezer et al., 2009; Raposo et al., 2006). One study also showed neural adaptation effects in the fusiform gyrus of bilingual participants, but only when words were repeated in the same language (Nakamura et al., 2010). When words were repeated in two languages (translation), neural adaptation was found in the left posterior middle temporal gyrus (Nakamura et al., 2010). In our study, both the VWFA and the left middle temporal gyrus were deactivated for the homographic word-pairs, suggesting that both of these regions were sensitive to orthographic similarity between Spanish and English words. The homograph condition cannot be compared directly to Nakamura and colleagues (2010) cross-language repetition condition, because homographs do not share meaning, as do translations. But, taken together, these findings may suggest that middle temporal gyrus is sensitive to amodal (either orthographic, or semantic) similarity between words in first and second language. In monolingual literature, posterior middle temporal gyrus activity has also been associated with wordform retrieval (e.g., Indefrey & Levelt, 2004). In our study, English homographs of Spanish targets primed the retrieval of the target word-forms and this could have produced a lower than usual amplitude of response in the posterior middle temporal gyrus.

In addition to VWFA and posterior middle temporal gyrus, deactivations were found in the left angular and inferior temporal gyri. The activity of the left inferior temporal gyrus is likely to be coupled with the adjacent inferior occipito-temporal gyrus (including the VWFA) and is, probably, related to word retrieval. Support for this claim comes from work by Gaillard and colleagues (2006) who showed that an epilepsy patient, who underwent a resection of inferior temporal and fusiform gyri, exhibited letter-byletter reading with longer latencies for longer words. Such a deficit implies that inferior temporal gyrus may contribute to the retrieval of whole words . Angular gyrus is another region that has been linked to both phonological analysis and word-form retrieval (e.g., Hillis et al., 2005). Decreased activity of angular gyrus has been associated with developmental phonological dyslexia, a disorder characterized by inability to read unfamiliar letter-sound combinations (Temple et al., 2001), suggesting that this area may support rule-based grapheme-to-phoneme conversion. Supramarginal gyrus, an area adjacent to angular gyrus, also participates in phonological processing (Abel et al., 2009; Jobard et al., 2003; Vigneau et al., 2006). Given the proximity of angular and supramarginal gyri, it is possible that these areas interact in supporting conversion of orthographic input into phonology and may help to bind orthographic and phonological representations with meaning.

Among other areas that were deactivated in the homograph condition are bilateral lateral occipital cortices. Lateral occipital cortex is thought to hold object knowledge (e.g., Caramazza & Shelton, 1998) and its activation in our study may be related to the processing of word meaning. Our reaction time results showed that Spanish words primed with their English homographs were recognized more slowly than Spanish words primed with unrelated English words. Thus, lexical retrieval may have been slower for homographs, resulting in slower activation of word meaning. This may explain the lower activation of the lateral occipital cortex in the homograph condition.

Similarly to our behavioral findings, neural priming effects for homographs were only observed in one direction of priming: I found homograph priming from English to Spanish, but not the reverse. As with behavioral studies of bilingual word reading, which show that for most bilinguals there is an asymmetry of cross-language interaction as a function of language experience and use (e.g., Kroll & Stewart, 1994); our results indicated that the VWFA de-activation may be modulated by stimulus-specific factors, such as target language proficiency, and potentially target language characteristics that impose particular processing demands. These notions will be discussed later when I consider patterns of effective connectivity across regions within the language network. Differences in the VWFA activity as a function of the language used for the prime indicate experience-based flexibility of this area.

In this experiment, the cognate pairs did not produce a deactivation of the VWFA, as did homograph pairs. What differentiates cognates from homographs is that, in addition to similar orthography, they share meaning in two languages. These findings challenge the functional specialization account showing that the VWFA is sensitive to more than just word forms. Our participants recognized Spanish words primed with cognates faster than words primed with homographs or unrelated words. They also recognized English words primed with cognates faster, than words, primed with their unrelated counterparts, suggesting that these bilinguals benefited from semantic overlap between English and Spanish during word retrieval. Semantic overlap also prevented neural adaptation of the VWFA. We found neural adaptation to pairs of homographs and not cognates. Why did we observe such a different response to cognates? It is possible, that cognates serve as important anchors in the bilingual's lexicon especially during early language acquisition. These lexical items are important for establishing commonalities between two language systems and as a result their processing may be enhanced. In contrast, homographs are a source of interference for the bilinguals. Finding different neural responses to cognates and homographs in the VWFA means that this area must either processes meaning or receive feedback from other areas which support semantic processing, for example, areas located in the anterior temporal lobe (e.g., Abel et al., 2009) and in the inferior prefrontal cortex (e.g., Francis, 1999; Jobard et al., 2003; Klein et al., 2006).

Several previous studies are in keeping with our finding that VWFA is sensitive to word meaning. For example, contrary to the often assumed pre-lexical function of this area, word frequency, which is considered to be a lexical-level variable, has been shown to modulate VWFA activity when processing words (e.g., Kronbichler et al., 2004). If words are processed in the VWFA as lexical units, rather than as word forms, they may automatically activate semantic and phonological representations (e.g., Rapp, Folk, & Tainturier, 2001). However, one recent report by Glezer and colleagues (2009) found no differences in processing pairs of semantically related words (*boat-ship*) and pairs of unrelated words in the VWFA. Thus, the increase in this area's activity to pairs of semantically related words may be mediated by similar orthography, supporting the notion that the VWFA is an integration area.

In monolingual English speakers, VWFA activity has been shown to decrease after sequential presentation of similar word forms, but not after sequential presentation of word forms that were close in meaning (Devlin et al., 2006). However, the study used words like "teacher" and "teach", which are somewhat similar, but non-identical in meaning. Words drawn from the same language such as those used in Devlin et al. study also differ with respect to morphosyntactic class (noun or verb) and, therefore, may be represented in distinct parts of cortex (e.g., Hauk, Johnsrude, & Pulvermüller, 2004). Our study avoided this issue by using bilinguals and drawing stimuli from two languages in order to control for this kind of semantic and morphosyntactic differences among stimuli.

There were two other notable results concerning the activity of the VWFA and several brain areas located in close proximity. First, there was no repetition-related suppression in the VWFA for repeated Spanish prime-target pairs. On the contrary, I found an increase in activation relative to the unrelated Spanish prime-target condition. This result is inconsistent with previous findings in monolingual speakers who show a decrease, rather than an increase, of the VWFA activity following word repetition (e.g., Glezer et al., 2009). The repetition-enhancement effect following presentation of pairs of identical Spanish words could be related to our participants' lower reading proficiency in Spanish. Having lower proficiency in a language is, essentially, like having many low-frequency words in one's lexicon (Finkbeiner et al., 2006). Previously, Henson (2001) observed neural suppression in fusiform regions for repeated familiar words and neural enhancement for repeated unfamiliar words. Our findings are consistent with this result, if we assume that printed Spanish words were less familiar to our participants, than printed English words. This is not an unreasonable assumption, given that our participants reported greater exposure to English in their daily lives (see Table 2.1).

A second notable finding was that during word recognition in English, translation prime-target pairs showed neural deactivation of inferior temporal cortex, relative to the unrelated prime-target pairs. However, this deactivation was located more medially and anterior to the location of the VWFA. Areas of deactivation included bilateral hippocampus and parahippocampal gyrus, lingual gyrus and parts of posterior fusiform gyrus. Deactivation of the anterior parts of the hippocampus and parts of perirhinal cortex has previously been associated with repetition priming and with skill learning, such as mirror-reading, (e.g., Poldrack & Gabrieli, 2001; Voss, Hauner, Paller, 2009). Hippocampus activity has also been linked to semantic and associative retrieval (e.g., Whitney et al., 2009) with activity in the medial and posterior hippocampus being correlated with an item's novelty. In general, hippocampus and surrounding cortices, especially the more anterior areas, likely subserve associative binding of stimuli into unified experiences (Whitney et al., 2009). Deactivation of hippocampus during translation priming in our study may be due to the fact that translations have been previously bound into a unified experience. This occurred at the time when our bilinguals learned these translation equivalents and may have been accompanied by an explicit word memorization. On the other hand, unrelated word pairs shown during our study represented a novel coupling of words in the bilinguals languages. Therefore, hippocampus was less active for targets primed with translations than targets preceded by unrelated words.

IMaGES Graphs

Previous studies of functional connectivity among the brain areas activated during reading revealed a language network that included left posterior fusiform gyrus (including the VWFA), inferior frontal gyrus, and superior temporal gyrus (Mechelli et al., 2005). A similar set of areas was identified by Vinckier and colleagues (2007). In their study, the VWFA, Broca's area, superior temporal sulcus and supplementary motor area were all sensitive to the degree of visual similarity of pseudoword stimuli to real words. Therefore, neuroimaging evidence suggests that no single brain area may be solely responsible for reading. Moreover, psycholinguistic models of reading posit that there may be multiple processing mechanisms underlying lexical access. For example, in Coltheart's cascaded model (Coltheart et al., 1993) there are two routes for lexical processing. First is the fast lexical route, which uses word-specific knowledge to quickly code word forms from orthography to meaning. This route is used for frequent and familiar words. The second route is the sub-lexical segment-by-segment route, which maps each grapheme to its phoneme and is used to decode unfamiliar or low-frequency words, which are not stored in the orthographic lexicon.

From the anatomical perspective, the presence of multiple routes for reading is supported by diffusion-tensor imaging studies which show that arcuate fasciculus, a white matter tract connecting the main parts of the language network, contains at least two parts. The first part is a direct pathway between temporal and frontal regions and the second part is an indirect connection, which traverses inferior parietal regions (Turken & Dronkers, 2011). Furthermore, functional imaging studies have shown considerable progress in linking lexical and sub-lexical processes with brain activation foci in the left hemisphere. For example, it was found that the AG may be a part of the indirect sub-lexical reading route described in Coltheart et al.'s (1993) model (e.g., Hillis et al., 2005). In support of this position, phonological dyslexics, who have difficulty reading novel letter-sound combinations, have an abnormally low level of activity in this area (Temple et al., 2001). Taken together this evidence suggests both a common language network, reliably activated during reading and some idiosyncratic variations reflecting differential reliance on reading sub-processes by different participant populations.

The results from our effective connectivity analyses revealed a set of common connections during early stages of processing for English and Spanish with a subsequent functional separation of language. The AG, the same area that shows differential activation as a function of reading skill level (e.g., Temple et al., 2001), mediated connections from the temporal lobe to the IFG whenever participants were reading Spanish, but not English target words. These differences in effective connectivity during reading of English and Spanish targets could be related to (1) participants' proficiency in each language, to (2) the processing demands imposed by each language, independently of language ability, or to (3) both of these contributors. To the extent that IFG is thought to be involved in language production and in semantic/syntactic processing (e.g., Hickok & Poeppel, 2004; Jobard et al., 2003; Klein et al., 2006), a direct connection to this area could signal a highly efficient processing mechanism with fast conduction between input (VWFA) and output (IFG) channels. On the other hand, an indirect connection to the IFG through AG, thought to house a set of conversion rules for single graphemes and phonemes, could indicate a slower decoding of written symbols into articulatory codes. This is in line with Coltheart's et al. (1993) conceptualization of the lexical route as the fast and automatic and the sub-lexical route as the slower and more laborious path to lexical access. English, a more proficient language for our participants, relied on the lexical route, whereas Spanish was processed via the sub-lexical route. Coltheart and colleagues argued that both routes are activated simultaneously. During processing of high-frequency words the lexical route always wins the race to lexical access, and so the output of the sub-lexical route is discarded. During processing of low-frequency words, the sub-lexical route provides candidate pronunciations and meanings, which compete for lexical selection. Finkbeiner et al. (2004) suggested that having a less proficient second language is like having many low-frequency words in one's lexicon. Consequently, the bilinguals' sub-lexical route will often win the race for lexical access.

Interestingly, Jamal et al. (2011) recently reported greater BOLD activation in the posterior superior temporal sulcus, an area directly adjacent to the AG, for Spanish over English, in bilingual participants who were matched in proficiency across the two languages. Thus, neural processing mechanisms required for Spanish may rely to a greater extent on the inferior temporal and parietal regions than those required for English. This finding suggests that language-specific factors, for example phonological

transparency, in addition to participants' language ability may contribute to the different effective connectivity patterns displayed by English and Spanish. Due to its more transparent mapping of graphemes to phonemes, Spanish may be more likely to engage the rule-based sub-lexical route (e.g., Jamal et al., 2011; Paulesu et al., 2000), whereas English, with its less consistent mapping from orthography to phonology, may need to rely more on the lexical route which is thought to process words as wholes. Therefore, both proficiency and language characteristics may affect neural processing during reading in bilinguals.

At the outset of these graphical analyses I predicted that neural activity in the VWFA would show qualitative differences in its interactions with parts of the reading network when processing cognates, than when processing homographs. In light of the localization results obtained in this experiment it was suggested that during cognate reading the VWFA may receive feedback activation from anterior semantic areas. The IMaGES analysis showed that activation of the posterior temporal regions (MTG) was, in fact, influenced by feedback projections from more anterior temporal areas, such as the TP, which has been implicated in semantic processing, (e.g., Abel et al., 2009). However this feedback projection was found across all conditions, suggesting that it cannot account for the differences in brain activation between cognates and homographs. This implies that either (1) semantic information is stored in the VWFA, or that (2) these effects arise as a result of more local interactions, for example, between anterior and posterior parts of the fusiform gyrus. The results of Experiments 1 and 2 pose a challenge to the former account. If language segregation is postponed until after activation reaches anterior temporal regions then it may be difficult to establish a one-toone mapping between orthography and meaning during the early processing in the VWFA, especially in the case of homographs, which have similar word forms and different meanings. One way that this could happen is by means of a phonological disambiguating process. Homographs are similar orthographically and, consequently are somewhat similar phonologically. However, phonetic features of words in Spanish and English differ and these sound cues could be used to select the correct semantic representation. Consistently with this idea, the connectivity analyses showed that Spanish homograph reading was associated with earlier activation of the Heschl's gyrus, a part of the primary auditory cortex, via the VWFA. Alternatively, the differences in processing of cognates and homographs could arise as a result of the interaction between the VWFA and more anterior parts of the fusiform gyrus and temporal lobe. Specifically, after the VWFA computed an abstract orthographic representation, this representation would be linked with semantic information through recurrent feedback cycles between posterior and anterior temporal regions. In previous work anterior fusiform gyrus and TP have been associated with semantic processing (Abel et al., 2009; Fiez & Petersen, 1998; Vigneau et al., 2006). It is likely that both processes take place, such that early cues to language membership are estimated in the VWFA and this information is later refined through the interactions of the VWFA with other brain areas involved in semantic and phonological processing.

As discussed earlier, according to the interactive models of visual word recognition in monolinguals (e.g., McClelland & Rumelhart, 1981) and bilinguals (e.g., Dijkstra & van Heuven), many orthographically similar word forms become activated during early stages of reading. For bilinguals, homographic word forms activate two distinct semantic representations, whereas cognate word forms activate a single semantic representation. Once a semantic candidate has been selected, the other alternatives are inhibited at the level of semantics and recursively at the level of orthography. At the same time, positive feedback activation is transferred to the orthographic entry linked with the selected semantic candidate. In Experiment 3, semantic feedback was enhanced for cognates due to a greater initial activation of the semantic entry from two orthographic sources (prime and target). This process prevented neural adaptation effects during cognate reading. For homographs, early facilitation of orthographic processing due to word form similarity between primes and targets led to strong activation of two different semantic entries, which subsequently inhibited each other. This inhibition decreased the amount of feedback activation received from anterior brain areas.

A result that is consistent with the notion that semantic effects arise in the VWFA as a result of local interactions within the left temporal lobe is the finding that the posterior MTG, area situated near the VWFA, mediated the TP projections to the IFG and AG in all but one case, which was the recognition of Spanish target words primed with English homographs. Posterior MTG was previously implicated in reading (Paulesu et al., 2000; Vingerhets et al., 2003), listening to a story (Abutalebi et al., 2007; Perani, et al., 1998; Perani et al., 1996) and making plausibility judgments about written sentences (e.g., Yokoyama et al., 2006). Nakamura et al. (2010) found repetition suppression of the posterior MTG in bilingual speakers following visual presentation of translation pairs. And Indefrey and Levelt (2004) associated this area with word-form retrieval processes. Together this body of work points to a role for the posterior MTG in processing of both word form and meaning information. In Experiment 3, the homograph interference may
have had its greatest impact on the TP, an area thought to process word meaning (e.g., Abel et al., 2009; Price, 2010). The TP in turn provided insufficient excitatory feedback to the posterior MTG, causing this area to decrease in activation relative to the control condition. This interpretation is consistent with our localization results, which show a suppression response in MTG during homograph reading.

Our participants did not show a behavioral interference effect in the other direction of priming, when homograph primes were presented in Spanish and target words were shown in English. This asymmetry in priming effects was discussed in previous sections in relation to the psycholinguistic models of word recognition and production in bilinguals, the BIA+ and the RHM. Similarly, neural results can be discussed in the context of the two models. For example, Experiment 1 and 2 showed that orthographic processing in fluent bilinguals relies on overlapping neural representations. This result is consistent with the BIA+ model. However, Experiment 3 further showed that subsequent processing may be segregated into distinct neural processing routes and this finding is more consistent with the RHM, which proposes that the two languages of a bilingual are functionally separate. Finally, a third finding may be difficult to reconcile with either of the models. According to both models behavioral asymmetries of cross-linguistic influence observed in bilinguals are a result of proficiency differences. However, the graphical analyses reported here suggest that these asymmetries may arise for languages, such as English and Spanish, as a result of more general processing demands. Specifically, the lack of priming from Spanish into English may be related to the fact that briefly presented and masked Spanish primes were not processed to the level of semantics. As noted before, Spanish targets were processed via

an indirect temporo-parietal-frontal route. Neuroimaging, clinical and linguistic evidence, as well as anatomical feasibility, all point to the involvement of this route in sub-lexical phonological processing. Therefore orthography-to-phonology conversion most likely occurred early for Spanish primes, whereas semantic processing was probably delayed. Considering the brief presentation window of the primes, it is likely that semantic processing was not completed for these stimuli and therefore did not produce a semantically-mediated interference. In contrast to Spanish targets, English targets were processed via a direct temporo-frontal connection which allowed fast and automatic access to meaning. The fast access to meaning, in turn, facilitated early semantic influences in visual word recognition for this language. This is why, when primed with English targets, our participants showed both the homograph interference and cognate facilitation effects. Needless to say that proficiency differences can modulate these processing mechanisms and can potentially inflate any asymmetries in cross-linguistic influences that exist naturally due to language-specific characteristics.

Neural results can be used to supplement and modify the existing psycholinguistic theories. For example, the revised BIA+ model postulates the existence of a separate task component involved in word recognition. This component deals with task-specific demands and is used to select an appropriate response given a particular task schema. According to Dijkstra and van Heuven (2002) the task component cannot directly influence the word identification system. In contrast, the word identification system provides input directly into the task component. This kind of asymmetrical relationship is an ad hoc addition to the model, which helps to explain enduring cross-linguistic interference effects across a variety of tasks. However, considering that languages with transparent orthographies (Hindi, Italian, Russian, Spanish) impose different processing constraints than languages with less transparent orthographies (English and French) and rely on different neural processing routes (e.g., e.g., Bick, Goelman, & Frost, 2011; Das, Padakannaya, Pugh, & Singh, 2011; Jamal et al., 2011; Paulesu et al., 2000), the relationship between task-demands and word identification may need to be revised in the BIA+ model if it is to be considered an accurate representation of the bilingual word recognition.

Another notable finding that can inform the behavioral models of word recognition in bilinguals is the early involvement of semantic processes in word recognition. In this experiment, the effects of semantic information were found in the VWFA an area thought to process orthography. Moreover, the existence of multiple pathways for reading suggests that brain areas supporting orthographic, phonological and semantic processing may be activated in parallel. Based on results of Experiment 3, it may be suggested that areas processing orthography and phonology may be co-activated early during word recognition in Spanish, followed by the activation of semantics. In English, areas processing orthography and semantics may be co-activated early, followed by the activation of phonology. This is consistent with the graphical analyses, which show that across all conditions Heschl's gyrus was activated earlier for Spanish than for English. Presumably, this area participates in phonological processing (e.g., Hickok & Poeppel, 2004) as it is part of the primary auditory cortex. Simultaneous activation of different language areas was noted by Schwartz et al. (1996) in their paper describing intracranial recordings in patients with epilepsy. The authors collected local field potentials while patients performed language tasks and found concurrent electrical

activity in electrode grids located over temporal and prefrontal areas. Cornelissen et al. (2009) also reported simultaneous activity recorded using MEG⁴ in mid-fusiform gyrus and left IFG during word reading. ERP evidence has also been used to show early semantic activation during reading (Penolazzi, Hauk, & Pulvermuller, 2007). These results are in contrast with the sequential nature of psycholinguistic models of reading and bilingualism and call for a re-assessment of these models in light of the mounting neural evidence.

Conclusion

The graphical analysis presented in Experiment 3 revealed dissociable neural networks for Spanish and English in fluent bilingual speakers. Spanish words engaged the angular gyrus, located along a dorsal route from the temporal lobe to frontal areas; while English relied on a more ventral connection from the temporal pole to the inferior frontal gyrus. These findings are consistent with a psycholinguistic dual-route model of reading (Coltheart et al., 1993). This study also extended previous work on the nature of neural processing in the Visual Word Form Area, a brain region thought to be functionally specialized for processing of orthographic stimuli. Similar to studies with monolinguals, I show here that the VWFA is modulated by word meaning in bilinguals. Although activation in this area decreased in response to pairs of homographs, it did not do so in response to pairs of cognates, suggesting that shared meaning buffered the VWFA against neural adaptation. These results support a role for the VWFA in integrating incoming orthographic information with meaning.

Chapter 5: The Effect of Sentence Congruency on the VWFA Activity

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⁴ MEG - Magneto encephalography

Experiment 4: Introduction

The function of the VWFA has generally been tested using single word reading (e.g., Cohen et al., 2002; Epelbaum et al., 2008; Gaillard et al., 2006; James et al., 2005; Jobard et al., 2003; Kronbichler et al., 2006; Nelson et al., 2009; Qiao et al., 2010; Puce et al., 1996; Reinke et al., 2008; Song et al., 2010; van der Mark et al., 2009; Vinckier et al., 2007; Wong et al., 2009). However, people's everyday experience with reading rarely involves words in isolation. Most often we encounter at least a pair of words (e.g., Warren Street, Smith Hall) or whole sentences (e.g., You've got mail!). In this context, a task of reading relies on computation of semantics and on satisfaction of syntactic constraints. Therefore, it is likely that during sentence reading activity in the wordreading system will be tightly coupled with brain areas that are involved in semantic and syntactic processing, namely the anterior temporal lobe and the inferior frontal gyrus (e.g., Sakai, 2005; Gorno-Tempini et al., 2004). Activity in these higher-order language areas may even drive predictive responses in the VWFA. For example, Cornelissen and colleagues (2009) showed that MEG signals in the inferior frontal gyrus peaked at the same time as signals in the left middle fusiform gyrus. The authors suggested that early activation of the left inferior frontal gyrus following presentation of word-like visual stimuli helps to prime the language system by initiating top-down anticipatory responses. It is, therefore, possible that neural activity in the VWFA reflects the influence of both visual input and predictive semantic/syntactic processing.

Results from Experiments 1 and 2 established that the VWFA responds to words at a level of abstraction, which does not segregate language membership. This suggests that neural activity in this region is not driven by visual input alone. Experiment 3 showed that its activity is modulated by stored lexical characteristics, such as meaning. Specifically, while neural adaptation was observed when Spanish targets were preceded by their English homographs, an effect which was, likely, due to perceptual priming or habituation; no such adaptation was found when Spanish targets were preceded by their English cognates. Given that cognate word-pairs share their visual word-forms and meaning (e.g., Dijkstra & Van Heuven, 2002); this finding indicates sensitivity of the VWFA to lexico-semantics.

Semantic congruence between sequentially-presented words is a salient characteristic, especially when words are congruent across languages. It gives rise to the so called *cognate facilitation effect* (e.g., Costa, Caramazza, & Sebastian-Galles, 2000). Such semantic congruence may stimulate anterior temporal areas, implicated in processing meaning (e.g. Abel et al., 2009), producing excitatory feedback activation of the VWFA (see Devlin et al., 2006 for a description of a similar processing mechanism in monolinguals). The results of Experiment 3 imply that when variables, such as semantic congruence between sequentially-presented words, become relevant, top-down influences overshadow bottom-up visual signals in driving the activity in the VWFA.

Semantic constraints become especially relevant during sentence reading. By the time a reader gets to the end of a sentence a relatively small set of plausible words that may complete the sentence become available in memory. Reading the final word in the sentence involves comparison of the visual input from print with the lexical candidates available in memory. When the final word does not match the expectations of the reader, surprise may ensue, as illustrated by longer fixation times recorded with eye-tracking (e.g., Duchowski, 2002). Studies that use single-word reading to investigate the nature of

neural activity in the VWFA may underestimate the effects of such top-down processing. Therefore, the proposed Experiment 4 is designed to measure how activity in the VWFA is influenced by semantic constraints in the context of a sentence.

Previous neuroimaging studies of sentence reading have used a violation paradigm to uncover the brain areas involved in syntactic and semantic processing. In this paradigm brain activity during reading of a grammatically or semantically sound sentence is compared with brain activity during reading of a grammatically or semantically incorrect sentence. For example Meyer and colleagues (2000) compared activations for grammatically incorrect sentences with those for grammatically correct sentences and found increases of neural activity for the incorrect sentences in the STG, bilateral IFG, left middle frontal gyrus (MFG) and superior frontal gyrus (SFG), postcentral gyrus, and right supramarginal gyrus (SMG). When comparing semantically congruent with incongruent sentences, such as "Yesterday, I sailed Todd's hotel to China", greater activations were found in the hippocampus and parahippocampal gyrus (PHG), AG, bilateral MTG and left IFG (e.g., Newman et al., 2001, Price, 2010; similar results in auditory modality Humphries et al., 2006). Kiel and colleagues (1999) also found activations in the anterior superior temporal sulcus (STS), inferior frontal sulci and gyri, as well as the left middle temporal sulcus during the reversed comparison of semantically incongruent with semantically congruent sentences. In a direct comparison of semantic to syntactic anomalies, where semantically implausible sentences were compared with sentences that contained incorrect verb agreement, activity in the bilateral AG, right MTG, left hippocampus and PHG, left inferior frontal sulcus and MFG, anterior SFG, middle cingulate, head of caudate and medial inferofrontal cortex were

found (Ni et al., 2000). The violation paradigm employed by these studies is particularly suited for testing the hypothesis proposed in Experiment 4: that neural activity in the VWFA reflects the influence of both visual input and predictive semantic/syntactic processing. If a semantic violation occurs at the end of the sentence, after neural activation has reached the anterior semantic and syntactic areas, then we may see a change in the VWFA activation due to a change in feedback from these areas. If the net effect of congruency is an increase in attention to relevant input and suppression of irrelevant input, then the orthographic processing in the VWFA will be enhanced following presentation of congruent sentences and suppressed following presentation of incongruent sentences.

Using a subcategorization violation during sentence reading (e.g., "The boys giggled <u>the nuns</u>."), Kuperberg *et al.* (2000) observed activation in the left inferior temporal gyrus (ITG) and fusiform gyrus; however they found an increased, rather than decreased activity in the fusiform gyrus for the sentences with subcategorization. Subcategorization, however, involves a number of processing mechanisms, including syntactic and lexico-semantic. Therefore, it is not clear how much of this activation was due to the congruency of the words in the sentence and not due to the interaction of these processes.

Sentence reading is also associated with greater convergence of brain activity in monolinguals and bilinguals. During single word reading greater activity was found in the bilinguals' dorsal precentral gyrus, IFG pars triangularis and pars opercularis, STG, and planum temporale (Jones, 2011). In contrast, largely overlapping areas were found during sentence reading in bilinguals and monolinguals (e.g., Kovelman, 2008;

Hernandez et al., 2007). The few differences during sentence reading between monolinguals and bilinguals that are reported are often of quantity, rather than quality. For example, bilinguals activated the left IFG to a greater degree than monolinguals, and this increase in activation was associated with decreased proficiency in a language (Kovelman, 2008). Kotz (2009) suggested that differences in the activation of the IFG are related to age of acquisition of a language, in addition to proficiency. Kotz argues that there exists a tradeoff between the activation of the IFG and STG during reading, such that early and proficient learners of a second language rely more on the STG, whereas late second-language learners, even those with high levels of proficiency, recruit IFG and the basal ganglia for syntactic processing in their second language. Aside from these adjustments in the amounts of activity in the IFG and STG, bilinguals seem to rely on similar processing mechanisms during sentence reading, as monolinguals. Thus, the findings from Experiment 4 carry implications for theories of neural processes supporting reading in both bilinguals and monolinguals.

In Experiment 4, neural activity of the VWFA was recorded while participants read sentences. Each sentence contained a target word from Experiment 3. Target words were either congruent or incongruent with the meaning of other words in the sentence. It was predicted that targets, which were congruent with sentence meaning, would produce an increase in the VWFA activity, because they would activate task-relevant semantic representations and induce positive feedback from anterior temporal cortices. Incongruent targets were predicted to produce a decrease in the VWFA activity, because they would activate task-irrelevant semantic representations. Importantly, for homograph targets I manipulated whether the meaning of the word in the same language, or in a different language was congruent with sentence semantics. For example, in the sentence "*The baker cut the hot pie*" the target *"pie"* is congruent with the rest of the sentence when it is read in English. But in the sentence *"The boy injured the right pie"* the target *"pie"* is congruent with the rest of the sentence only if *"pie"* is read as a Spanish word (meaning "foot"). It was expected that in this condition, participants would have to recruit the dorsal route (VWFA-AG-IFG) for processing the Spanish target, as they did in Experiment 3.

Half of the sentences used in Experiment 4 contained a language switch. This switch was made to test if the VWFA was tracking surface level visual features during sentence reading. If this area responded primarily to the orthographic form of the stimuli then we would expect to see differences in its activity as a function of whether the sentence was all in the same language or contained a language switch. If, however, it responded to more abstract lexical elements and was primarily tracking consistency between the visual inputs and meaning, it would primarily, respond to sentence congruency and not to language switching.

Given that the VWFA is thought to only process orthographic word-forms, the findings of Experiment 4 were expected to expand the current understanding of neural processing in this area. Activity in the VWFA was examined in the context of its interactions with brain areas, which support lexical and semantic processing. Accounting for such interactions is critical when considering the function of the VWFA (e.g., McIntosh et al., 1999).

Method

Participants

The participants recruited for Experiment 2 also participated in Experiment 4. <u>Materials</u>

The cognate and homograph stimuli from Experiment 3 were used in Experiment 4. Each word was inserted into a (Subject-Verb-Object) sentence into the object position. For example, "The customer wore a *blouse*", where "blouse" is a Spanish-English cognate, or "The milk stained the *carpet*", where "carpet" is a Spanish-English homograph (Sp. *carpeta* - Engl. *folder*). In such manner, 30 sentences were constructed in each language and for each stimulus type (cognates vs. homographs) for a total of 120 sentences. In half of the sentences, the object (cognate or homograph) was in the same language as the rest of the sentence and in the other half of the sentences it was in a different language. An additional 120 sentences were created, such that the cognates and homographs in the object position did not match semantic composition of the rest of the sentence a *carpet*". A schematic illustration of the design is provided in Table 5.1.

Table 5.1:	Experimental	design in Ex	periment 4.
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	English Sentence			Spanish Sentence			
Englis	h Ending	Spanis	h Ending	English Ending		ing Spanish Ending	
Cognate	Homograph	Cognate	Homograph	Cognate	Homograph	Cognate	Homograph

Spanish sentences were first created in English and then were translated using an online dictionary. The quality of the translations was verified and any mistakes were

corrected by a faculty member at the Spanish and Portuguese Studies department at Rutgers University. In addition, a fluent Spanish-English bilingual, blind to the experimental manipulation, rated the Spanish sentences on 4 aspects: (1) whether the sentence was clear; (2) whether the rater was likely to use a similar sentence in speech (3) whether the rater was likely to hear a similar sentence from others (4) whether the rater would understand a sentence when spoken by others. This was done to ensure that the sentences in the congruent condition were considered more acceptable on these dimensions than the incongruent sentences. The rating scale was between 0-4 for the first 3 questions and between 0-3 for the last question, where 0 was labeled as "not at all"/"not at all likely"/"no" and 4 (or 3) was labeled as "completely"/"very likely"/"yes, completely" (see Table 5.2 for results).

Sentence Type	Clarity	Likelihood of Use	Likelihood of Encounter	Likelihood of Understanding in Speech
Congruent	2.05 (.63)*	1.43 (.37)*	1.47 (.36)*	1.71 (.44)*
Incongruent	1.61 (.4)	1.15 (.21)	1.20 (.29)	1.37 (.35)

Table 5.2: Ratings (and their standard errors) of Spanish sentences by a blind coder

Note: * significantly different at α =.05

Procedure

Testing for Experiment 2 and Experiment 4 took place on separate days. Prior to the scanning session, each participant completed a set of practice trials, during which feedback was provided. Participants were asked to read sentences presented on the screen and to decide whether each sentence was meaningful. They were told that the last word was crucial in deciding whether a given sentence was meaningful and that this word could appear in either English or Spanish. They were told to pay attention to the sentence and, if it was meaningful, to press the top button on the response box. They were asked to do so even when the last word in the sentence was written in a different language. Participants were provided with examples of meaningful and meaningless sentences (e.g., "The baker cut the pie", "The backer cut the truck", respectively). They were also given an example of when the last word could be consistent with the rest of the sentence, but only in one language. In the example "The boy injured his pie", they were asked to consider both the English and the Spanish reading of the homograph "pie" (Sp. foot). In cases, such as this one, they were asked to read the last word in both languages, and if in one language the meaning of the last word was consistent with the rest of the sentence they were asked to respond that the sentence was meaningful. When the sentences were not meaningful the participants were asked to press the second button from the top of the response box. They were asked to read each sentence carefully and respond when the sentence disappeared from the screen. No feedback was provided during this part of the study.

Images were presented back-projected onto a screen and reflected in a mirror in the head coil of the fMRI scanner. The timing of stimulus presentation was controlled by the PyEPL software (Geller, Schleifer, Sederberg, Jacobs, & Kahana, 2007). Each stimulus was presented for 6 seconds, followed by a response period. The response period was marked by a blank screen and was terminated when participants made a response, or, if no response was recorded, after 5 seconds passed. Trials were separated by fixation screens presented for 4 seconds and jittered for 4 seconds. Stimulus presentations were blocked with respect to language, target type (homograph vs. cognate) and language consistency (same language, different language ending) to increase signalto-noise ratio across conditions. Within a given block the trials were randomized with respect to sentence congruency. Total trial duration was approximately 8 seconds with an inter-stimulus interval lasting an average of 6 seconds. The order of block presentations was randomized. Reaction time, accuracy and brain activity were recorded during the experiment. Participants completed a total of 240 trials, separated into 8 blocks. Each block lasted approximately 6 minutes and was recorded as a separate run on the fMRI scanner.

fMR Image Acquisition and Analysis

The same procedures were followed as in Experiment 2 in acquiring and analyzing the BOLD data. 8 functional imaging runs were obtained for each participant in the course of the experiment. Each run was first analyzed at the individual level and then served as input into the group mixed-effects GLM model, where onsets of the sentences served as predictors of the BOLD response.

IMaGES Analysis

Similarly to Experiment 3, in Experiment 4 I conducted a graphical effective connectivity analysis using IMaGES (Ramsey et al., 2010). Timeseries of activation were compared for Spanish sentences which contained cognates and Spanish sentences, which contained homographs. Activation maps showed that the VWFA activity differed as a function of these conditions and the purpose of this analysis was to better understand the brain dynamics which were driving this activation difference.

Regions of interest (ROI) for the graphical analysis were selected based on areas found to be more active during reading of Spanish sentences with English homographs than while reading Spanish sentences with English cognates. Clusters of activation were separated into anatomical areas by means of intersecting them with anatomical regional masks from the Harvard Oxford Cortical Atlas. In such manner, ROIs in the VWFA, supramarginal gyrus, precuneous cortex, temporo-occipital part of the MTG, superior and inferior lateral occipital cortex (LOC) were created. In addition, ROIs in the IFG (pars opercularis and pars triangularis), posterior MTG, and Heschl's gyrus (HG) were selected based on previous research and the graphical analyses in Experiment 3. Average timecourses of neural activity were then extracted from each participant's raw BOLD data from all of the ROI locations and entered into the IMaGES model. Directionality of functional connections between areas was determined using the LOFS algorithm.

Results

Behavioral Results: Reaction Time

Repeated measures 2 x 2 x 2 x 2 x 2 ANOVA with language (English vs. Spanish), stimulus type (cognate vs. homograph), congruency (congruent sentences vs. incongruent sentences) and language switching (all same language vs. language switched on the last word) as factors was conducted. There was a main effect of congruency (F_1 (1, 11) =9.44, p<.05; F_2 (1,224) =7.87, p<.01): participants responded to congruent sentences (M=889.37, SE=99.49) faster than to incongruent sentences (M=981.97, SE=101.09). The analysis also showed a two-way interaction between congruency and stimulus type (F_1 (1, 11) =5.33, p<.05; F_2 (1,224) =2.87, p=.092), such that sentences with cognates (M=833.40, SE=129.35) were processed faster than sentences with homographs (M=945.34, SE=114.48), but only among congruent sentences. There were no differences between cognates and homographs among the incongruent sentences. A twoway interaction was also found between congruency and language switching ($F_1(1,11)$ =8.36, p<.05; $F_2(1,224)$ =3.66, p=.057), such that participants were slower to respond to same language sentences (M=1037.70, SE=136.23) than to sentences that had a language switch (M=926.24, SE=130.66), but only in the incongruent condition; in the congruent condition, there were no reaction time differences as a function of language switch (see Figure 5.1 for more details).





Figure 5.1: Reaction time and accuracy for sentence congruency decisions in Experiment 4 Error bars represent standard errors.

Behavioral Results: Accuracy

Repeated measures 2 x 2 x 2 x 2 x 2 ANOVA with language (English vs. Spanish), stimulus type (cognate vs. homograph), congruency (congruent sentences vs. incongruent sentences) and language switching (all same language vs. language switched on the last word) as factors was conducted. There was a main effect of language ($F_1(1,11)=30.52$, p<.001; $F_2(1,224)=15.09$, p<.001): English sentences (M=.87, SE = .01) were processed more accurately, than Spanish sentences (M=.77, SE=.01); and a main effect of stimulus type ($F_1(1,11)=7.60$, p<.05; $F_2(1,224)=1.92$, p=.177): sentences with cognates (M=.84, SE=.01) were processed more accurately, than sentences with homographs (M=.80, SE=.01).

There was a two-way interaction between congruency and stimulus type $(F_l(1,11)=37.92, p<.001; F_2(1,224)=8.98, p<.01)$, such that the accuracy advantage for sentences with cognates (M=.85, SE = .02) over sentences with homographs (M=74, SE=.02) was only observed in the congruent condition, in the incongruent condition the opposite trend was observed $(M_{cognates}=.82, SE_{cognates}=.02; M_{homographs}=.86, SE_{homographs}=.02)$. Another two-way interaction was found between language and stimulus type $(F_l(1,11)=25.01, p<.001; F_2(1,224)=4.68, p<.05)$: sentences with cognates (M=.82, SE=.02) were recognized more accurately than sentences with homographs (M=.82, SE=.02) in English, while in Spanish, the two sentences types were recognized with similar accuracy $(M_{cognates}=.76, SE_{cognates}=.01; M_{homographs}=.78, SE_{homographs}=.01)$. A third two-way interaction was found between language switching $(F_l(1,11)=5.35, p<.05; F_2(1,224)=10.00, p<.01)$: English sentences with a language switch (M=.83, SE=.02) were processed less accurately than all-English sentences

(M=.91, SE=.01), whereas Spanish sentences with a language (M=.81, SE=.01) switch were processed more accurately than all Spanish sentences (M=.73, SE=.02).

Three way interaction were also observed between congruency, language and stimulus type ($F_1(1,11)=5.35$, p<.05; $F_2(1,224)=1$, p=n.s.) and between language, stimulus type and language switching ($F_1(1,11)=7.38$, p<.05; $F_2(1,224)=3.15$, p=.077), showing that accuracy levels differed across these variables (see Figure 5.1).

Activation Maps

Effect of Sentence Congruency: Spanish

When participants read congruent Spanish sentences that contained homographs in Spanish they activated anterior MTG, bilateral planum polare, bilateral insula, and bilateral caudate nucleus (See Figure 5.2 and Table 5.3). In addition, areas of activation were found in the thalamus with peak activity centered on the anterior thalamic radiation, which projects primarily to the temporal lobe (60% of the projections); pre-frontal regions (22% of the projections) and to the occipital lobe (14% of the projections; from JHU White-Matter Tractography Atlas available as part of the FSL Software package). Activations in the frontal and central operculum, including IFG and insula, included white matter tracts which are part of the uncinate and superior-longitudinal fasciculus and activations in the putamen and caudate nucleus were part of the inferior fronto-occipital fasciculus and of the anterior thalamic radiation.

Table 5.3: Local maxima of neural activation during sentence reading in Spanish. Each activation peak is described by a *z*-statistic, related to the intensity of activation and x, y, z coordinates in standard Montreal Neurological Institute (MNI) brain space.

Harvard-Oxford Cortical Structural Atlas or MNI Atlas Label	z-statistic	x	У	Z
Spanish Sentences with Homographs: Congruent > Incongruent				
Right Thalamus	2.75	3	-10	5
Right Thalamus	2.74	3	-12	5
39% Central Opercular Cortex, 10% Precentral Gyrus, 3% Inferior Frontal Gyrus, pars opercularis	2.72	51	2	8
47% Putamen, 9% Caudate	2.72	22	21	2
63% Frontal Pole, 3% Frontal Orbital Cortex	2.72	22	42	-20
54% Insular Cortex, 21% Frontal Operculum Cortex, 6% Central Opercular Cortex	2.71	-32	12	10
Spanish Sentences with Cognates : Congruent > Incongruent				
100% Putamen	3.22	28	9	1
17% Insula, 3% Putamen	3.06	35	1	8
46% Thalamus	2.99	2	-4	8
48% Putamen	2.93	23	1	8
36% Right Cerebral White Matter, 16% Right Amygdala, 4% Right Cerebral Cortex	2.93	14	-9	-12
76% Right Cerebral White Matter, 17% Right Pallidum, 3% Right Cerebral Cortex	2.93	11	-5	-7
32% Middle Temporal Gyrus, posterior division, 19% Superior Temporal Gyrus, posterior division, 8% Middle Temporal Gyrus, anterior division, 3% Superior Temporal Gyrus, anterior				
division	2.95	-56	-17	-8
4% Putamen, 4% Insula	2.95	-29	6	15
95% Left Putamen, 3% Left Pallidum	2.94	-19	7	-4
91% Left Putamen, 3% Left Pallidum	2.93	-19	6	-7
64% Left Cerebral White Matter, 21% Left Putamen	2.93	-18	8	6
25% Middle Temporal Gyrus, posterior division, 22% Superior Temporal Gyrus, posterior division, 9% Middle Temporal Gyrus, anterior division, 3% Superior Temporal Gyrus, anterior				
division	2.92	-59	-17	-7



Figure 5.2: Clusters of activity for congruent relative to incongruent Spanish sentences. Group-level z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.96 and a (corrected) cluster significance threshold of p=.05. A) Spanish Sentences with homographs; B) Spanish sentences with cognates.

When participants read Spanish sentences with contained cognates in English they activated bilateral putamen, bilateral insula and Heschl's gyrus, bilateral STG and precentral gyrus, right IFG, right lingual and right parahippocampal gyrus, as well as parts of ventro-medial pre-frontal cortex (see Table 5.3). The activations in the thalamus

were along the white fiber tracts projecting primarily to the temporal (47%) and the occipital (3%) lobes. The activations in the insula and putamen were along the superior longitudinal fasciculus and inferior fronto-occipital fasciculus.

Effect of Sentence Congruency: English

While reading congruent English sentences which contained homographs in Spanish participants activated areas in the parietal and occipital lobes, including the intracalcarine cortex, lingual gyrus, occipital pole, lateral occipital cortex, cuneal and precuneous cortex bilaterally. In addition, centers of activity were found in the AG and the posterior supramarginal gyrus. This activation was observed when congruent sentences were compared with incongruent sentences (see Table 5.4 and Figure 5.3). While reading congruent English sentences which contained cognates in English, participants activated superior parietal areas, including the precuneous cortex and posterior cingulate gyrus (see Table 5.4 and Figure 5.3).

Table 5.4: Local maxima of neural activation during sentence reading in English. Each activation peak is described by a *z*-statistic, related to the intensity of activation and x, y, z coordinates in standard Montreal Neurological Institute (MNI) brain space.

Harvard-Oxford Cortical Structural Atlas or MNI Atlas Label	z-statistic	x	У	Z
English Sentences with Homographs: Congruent > Incongruent				
44% Intracalcarine Cortex, 23% Lingual Gyrus	3.24	7	-70	7
29% Occipital Pole, 17% Intracalcarine Cortex, 10% Cuneal Cortex, 4% Supracalcarine Cortex, 1% Lateral Occipital Cortex, superior division	2.94	9	-89	11
25% Cuneal Cortex, 5% Lateral Occipital Cortex, superior division, 3% Precuneous Cortex	2.87	-14	-83	29
29% Lateral Occipital Cortex, superior division, 6% Cuneal Cortex, 1% Occipital Pole, 1% Precuneous Cortex	2.86	-18	-84	29

38% Lateral Occipital Cortex, superior division, 9% Occipital Pole, 3% Cuneal Cortex, 1% Precuneous Cortex	2.86	-17	-86	27
55% Occipital Pole, 2% Supracalcarine Cortex, 2% Intracalcarine Cortex	2.84	5	-96	9
61% Angular Gyrus, 19% Supramarginal Gyrus, posterior division, 9% Lateral Occipital Cortex, superior division, 3% Middle Temporal Gyrus, temporooccipital part	2.53	-60	-55	-21
English Sentences with Cognates: Congruent > Incongruent				
57% Precuneous Cortex, 16% Cingulate Gyrus, posterior division	3.01	1	-53	37
65% Cingulate Gyrus, posterior division, 22% Precuneous Cortex	2.99	9	-48	33
73% Precuneous Cortex, 24% Cingulate Gyrus, posterior division	2.98	3	-47	42
64% Precuneous Cortex, 33% Cingulate Gyrus, posterior division	2.95	4	-48	40
72% Precuneous Cortex, 26% Cingulate Gyrus, posterior division	2.95	3	-54	35
43% Precuneous Cortex, 26% Cingulate Gyrus, posterior division	2.95	1	-49	38

Effect of Stimulus Type Averaged across Levels of Congruency

No differences were observed for English sentences with cognates relative to English sentences with homographs when brain activations were averaged across levels of congruency. For Spanish sentences, greater activation for homographs relative to cognates was found in the anterior frontal regions, bilateral IFG (pars triangularis) located near the inferior fronto-occipital fasciculus fiber tract (18% overlap) and anterior thalamic radiation (3% overlap), left caudate nucleus also including parts of the anterior thalamic radiation, right Heschl's gyrus and left thalamus with projections to pre-motor (72%), pre-frontal (40%), posterior parietal (13%) and primary motor cortex (4%).



Figure 5.3: Clusters of activity for congruent relative to incongruent English sentences. Group-level z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.96 and a (corrected) cluster significance threshold of p=.05. A) English Sentences with homographs; B) English sentences with cognates.

In addition, parts of left thalamus projecting to temporal (74%), occipital (26%) and prefrontal (16%) cortex were activated. A cluster of activity was also found in the anterior cingulate cortex and an extended cluster covering a projection from left caudate to the frontal opercular cortex via the anterior limb of the internal capsule was observed. For Spanish sentences with English endings, greater activations for homographs were found in the bilateral AG, left MTG, parietal operculum, supramarginal gyrus, left planum

temporale and in the VWFA (see Table 5.5 and Figure 5.4).

Table 5.5: Local maxima of neural activation during sentence reading in Spanish. Each activation peak is described by a *z*-statistic, related to the intensity of activation and x, y, z coordinates in standard Montreal Neurological Institute (MNI) brain space.

Harvard-Oxford Cortical Structural Atlas or MNI Atlas Label	z-statistic	x	у	Ζ	
Spanish Sentences: Homographs > Cognates					
40% Left Cerebral White Matter, 21% Left Accumbens, 8% Left Pallidum, 8% Left Caudate	3.96	-10	6	-5	
79% Left Frontal Pole	3.82	-22	58	0	
59% Right Frontal Pole	3.69	33	54	3	
64% Frontal Pole	3.69	32	56	3	
48% Frontal Pole	3.67	32	52	3	
44% Frontal Pole	3.65	14	64	10	
Spanish Sentences with English Endings: Homographs > Cognates					
9% Occipital Pole, 7% Lateral Occipital Cortex, superior division	4.55	15	-88	47	
6% Occipital Pole, 4% Lateral Occipital Cortex, superior division, 2% Cuneal Cortex	4.47	13	-89	46	
10% Lateral Occipital Cortex, superior division, 2% Occipital Pole	4.44	18	-87	48	
3% Occipital Pole, 1% Lateral Occipital Cortex, superior division	4.4	15	-91	45	
36% Lateral Occipital Cortex, superior division	4.35	18	-82	52	
26% Lateral Occipital Cortex, superior division	4.32	14	-81	53	
19% Temporal Occipital Fusiform Cortex, 2% Temporal Fusiform Cortex, posterior division, 1% Inferior Temporal Gyrus, temporooccipital part, 1% Inferior Temporal Gyrus, posterior division	2.99	-37	-52	-9	



Figure 5.4: Clusters of activity for homographs relative to cognates in Spanish sentences. Group-level z (Gaussianised t/F) statistic images were thresholded using clusters determined by z>1.96 and a (corrected) cluster significance threshold of p=.05. A) Spanish Sentences with homographs in Spanish; B) Spanish sentences with homographs in English.

IMaGES Graphs

The graphical analysis was performed on the timecourses of brain activity during reading of Spanish sentences with English homographs and Spanish sentences with English cognates. Throughout this experiment, participants' task was to check the meaning of the final word in both languages before making the congruency decision. Importantly, participants were instructed to judge sentences as congruent even when the final word had to be read in a different language. This created different processing demands in the cognate and the homograph conditions. The kind of conflict resolution which resulted from activating competing homograph meanings in two languages was not required when reading sentences with cognates because cognates have the same meaning across languages, and are thought to share their conceptual representations (e.g., Dijkstra & Van Heuven, 2002).

Additional processing required in the homograph condition may have contributed to the different patterns of interaction observed between areas in the reading network. A cascade of top-down activations from prefrontal language areas to more posterior extrastriate and temporal lobe regions was found in the homograph condition. One path descended from IFG pars opercularis to the temporal occipital fusiform gyrus (TOFC; the location of the VWFA) via pars triangularis. Another went directly from pars opercularis to the temporo-occipital part of the MTG, an area adjacent to the VWFA. Reading sentences with homographs was also characterized by local interactions within the posterior temporal and occipital areas and a lack of feed forward connections to the prefrontal cortex. This result was consistent with the GLM analysis, which showed no significant activations in the prefrontal areas.

Conversely, in the cognate condition, feed-forward projections from TOFC were found to the IFG pars opercularis via temporo-occipital MTG. Another feed-forward projection was found from the posterior MTG to the IFG pars triangularis via SMG. In fact, MTG served as a relay hub in the cognate condition, connecting posterior MTG with IFG and superior LOC. This was different from its modulating role in the homograph



condition, where it projected to both the temporo-occipital MTG and to superior LOC (see Figure 5.5).

Figure 5.5: IMaGES graphs for Spanish sentences with English homographs and English cognates. Hg – Heschl's gyrus; ifg_op – inferior frontal gyrus pars opercularis; ifg_tr – inferior frontal gyrus pars triangularis; loc_inf – lateral occipital cortex, inferior division; loc_sup – lateral occipital cortex, superior division; mtg_post – middle temporal gyrus, posterior division; mtg_to – middle temporal gyrus, temporo-occipital cortex; precun – precuneous cortex; smg_post – supramarginal gyrus, posterior division; tofc – temporal occipital fusiform gyrus.

The models obtained with IMaGES were tested on each participant's data using a

Chi-square test and were found to be significant across all participants (p<.0001).

Average regression coefficients for each directed connection are provided in Table 5.6.

Connection	From	То	Regression weight	Standard Error	t-score	Probability
Sentences with H	lomographs					
B1	IFG op	IFG tr	0.88	0.05	21.19	<.001
B2	IFG op	MTG to	0.35	0.05	6.91	<.001
B3	IFG tr	TOFC	0.28	0.05	6.18	<.001
B4	LOC sup	Precun	0.60	0.07	8.47	<.001
B5	LOC sup	TOFC	0.16	0.04	5.01	<.001
B6	MTG to	MTG post	1.21	0.09	12.35	<.001
B7	MTG to	HG	1.17	0.10	13.26	<.001

Table 5.6: Regression coefficients for the models of effective connectivity.

5.0	1 (77.6	T 0 0 : 0	1.2.4	2.22	10.05	2.2.1
B8	MTG to	LOC inf	1.36	0.08	18.85	<.001
B9	MTG to	Precun	0.72	0.13	6.08	<.001
B10	SMG post	MTG to	0.27	0.04	8.28	<.001
B11	SMG post	LOC sup	0.94	0.05	23.32	<.001
Sentences with	Cognates					
B1	HG	MTG to	0.17	0.03	5.99	<.001
B2	IFG tr	IFG op	0.69	0.05	16.50	<.001
B3	LOC inf	MTG to	0.40	0.04	10.97	<.001
B4	MTG post	SMG post	-0.12	0.10	-1.22	=.13
B5	MTG to	MTG post	0.93	0.09	9.95	<.001
B6	MTG to	IFG op	0.30	0.08	4.83	<.001
B7	MTG to	Precun	1.05	0.15	8.11	<.001
B8	Precun	LOC sup	0.14	0.04	3.64	<.001
B9	SMG post	IFG tr	-0.003	0.08	0.84	n.s.
B10	SMG post	LOC sup	0.81	0.06	17.48	<.001
B11	TOFC	MTG to	0.18	0.05	3.58	<.001

Discussion

Behavioral Results

Participants identified congruent sentences faster than incongruent sentences. Moreover, they identified sentences with cognates faster and more accurately than sentences with homographs. This provides additional support for the cognate facilitation and homograph interference effects at the sentence level. Interestingly, the cognate advantage was primarily due to processing of congruent sentences. The opposite effect was observed when participants were reading incongruent sentences. The fast recognition of cognates actually produced interference in this case. Behavioral results also indicated that participants were better at reading in English, than in Spanish. English sentences were identified more accurately than Spanish sentences. This was not due to a speed-accuracy trade off because both English and Spanish sentences were processed at the same speed. The cognate advantage was also observed to a greater degree for English, than for Spanish. Moreover, while language switching decreased accuracy during English sentence reading, it improved accuracy during Spanish sentence reading. This effect suggested that participants had difficulty reading Spanish sentences and benefited when Spanish sentences contained English words. Taken together, the behavioral results suggested that participants were more practiced in reading English, which is not surprising, given that they were enrolled as students at an American university at the time of the study. Both reaction time and accuracy measures showed decrements when interference was introduced by ways of either semantic inconsistencies or language switching; and this interference was more pronounced when participants were reading in the more practiced language.

Activation Maps

Congruency Effects in Spanish

The effects of congruency for Spanish sentences were found in a number of subcortical structures, including putamen, caudate nucleus, insula and thalamus. These subcortical structures were co-activated with cortical regions, such as the IFG pars opercularis, MTG, precentral cortex and frontal pole. It is well known that the basal ganglia (putamen and caudate nucleus) belong to a set of anatomically segregated parallel circuits, connected with distinct part of cortex via the thalamus (e.g., Groenewegen, Galis-de Graaf, & Smeets, 1999). The circuits are sometimes segregated functionally into motivational, executive, visual and motor loops (Lawrence et al., 1998). The connections through the caudate nucleus to the temporal cortex belong to the visual sub-division. The connections through putamen to the premotor cortex belong to the motor sub-division and connections through the caudate nucleus to dorsolateral prefrontal cortex are thought to belong to the executive sub-division. All of these areas were

activated when participants read Spanish sentences. Interestingly, the parts of the thalamus that were activated were the parts connecting to the prefrontal cortex, and to motor, parietal and temporal cortexes. Therefore, in Experiment 4 participants were recruiting their motor, visual and executive circuits to a greater degree when reading in Spanish.

Previous studies have associated activations in the subcortical structures like the putamen and insula with increased articulatory demands. For example, Meschuyan and Hernandez (2006) found activations in the supplementary motor area, cingulate, putamen and insula in Spanish-English bilinguals when they were reading in their less proficient language (Spanish). Kumar *et al* (2010) saw increases in the activity of the putamen and thalamus in Hindi-English bilinguals, when they were overtly reading phrases in English, which was their weaker language. When participants were reading in Hindi, they activated insula, associated with motor planning (Dronkers, 1996) and the caudate nucleus. The caudate nucleus has previously been implicated in visuo-spatial learning, such as reading a mirror-reversed script (Poldrack et al., 1998; Dong et al., 2000).

Activation of these structures in Experiment 4 may be due to lower reading fluency of participants in Spanish. Furthermore, given evidence from Kumar et al. (2010) study, it may indicate that participants were articulating Spanish sentences subvocally during reading.

Congruency Effects in English

While reading English sentences participants activated parietal attention areas such as cuneal cortex, the precuneus and the PCC for congruent sentences more than for incongruent sentences. They also activated visual cortexes more for congruent sentences

than for incongruent sentences. The posterior parietal areas including cuneus and precuneus have cortico-cortical projections to the frontal cortex and their functions are related to shifting attention and motor planning (see Cavanna & Trimble, 2005 for review). These patterns of activity suggest that the participants were not engaged in sub-vocal reading, as they were when reading in Spanish. These activations may have been related to attending to the stimuli and preparing to make a button press response. Interestingly, when participants read English sentences with Spanish homographs, in addition to these attention-related activations, they showed a significant activation in the AG. This finding is consistent with the predictions for Experiment 4. At the outset of Experiment 4, it was predicted that homograph targets that are congruent, if read in Spanish, would activate the indirect dorsal route, as was found in Experiment 3. On these trials, in order to make the correct decision, participants were required to switch between the orthography-to-phonology conversion rules for English to those for Spanish. And the orthography-to-phonology rule system is thought to be located in the angular and supramarginal gyri (e.g., Hillis et al., 2005; Temple et al., 2001; Carreiras et al., 2009). This was especially true for semantically congruent Spanish homograph in an English sentence. For English sentences with Spanish cognates there may not have been a decision conflict because cognates share their meaning in the two languages.

Activation Maps: Effect of Stimulus Type

It was predicted that in Experiment 4, congruent targets would produce an increase in the VWFA activity and the incongruent targets would decrease the VWFA activity. Congruent cognate and homograph targets were expected to activate task-relevant semantic representations and produce positive feedback from semantic areas to

the word-form reading system. In contrast incongruent cognate and homograph targets were anticipated to generate negative feedback and a suppression of the word-form system. However, the hypothesis that the VWFA is modulated by sentence level congruency was not supported. Instead, the VWFA activity was related to the interaction between language and stimulus type.

The VWFA responded differently to cognates than to homographs when participants were reading Spanish sentences. Specifically, this region was more active when participants read Spanish sentences that contained *homographs* in English than when they read Spanish sentences that contained *cognates* in English. This experimental context is similar to Experiment 3 where the VWFA showed repetition suppression to Spanish words primed by English *homographs*, but not to Spanish words primed by English *cognates*. Together, these findings suggest that the VWFA is sensitive to the difference between cognates and homographs in the context of bilingual reading, i.e., when both English and Spanish words are present. Unlike the Experiment 3, in Experiment 4 there was an increase in activation of this area for sentences with homographs. This could be due to methodological differences between the experiments: in Experiment 3 a primed lexical decision task was used, and in Experiment 4 a sentence reading task was used, where words were not repeated. To better understand the differences in processing between cognates and homographs in Experiment 4, a graphical effective connectivity analysis was conducted using IMaGES (Ramsey et al., 2010).

IMaGES Analysis

The graphical analyses supported the notion that activity in the VWFA was tightly coupled with activity in the anterior language areas, such as the IFG. Different patterns of their interactions were observed for homographs and cognates. Specifically, feed forward projections from TOFC to the temporo-occipital MTG and then to IFG pars opercularis in the cognate condition were in contrast with feedback connections from the IFG pars opercularis and triangularis to the TOFC and temporo-occipital MTG in the homograph condition. This finding is consistent with the notion that both visual input and feedback projections from areas in the language network drive the activity in the VWFA. However, when considering activation maps and graphical analyses together, it seems that the top down projection from the prefrontal areas to the VWFA was excitatory, rather than inhibitory. Homographs showed increased activation relative to cognates. This is contrary to the notion that incongruent information is inhibited. Instead, it indicates increased visual attention to the incongruent stimulus. Moreover, it is in apparent conflict with findings in Experiment 3, where there was a habituation response to repeated homographs.

There is an important difference in the procedures used in Experiment 3 and those employed in Experiment 4. Whereas the lexical decision task in Experiment 3 could have been accomplished using orthographic processing alone, the sentence task in Experiment 4 could not. The sentence congruence decision required participants to focus on the meaning of the words in the sentence. Participants paid particular attention to homographs, because these stimuli activated inconsistent semantic representations in two languages. Participants had to inhibit the urge to decline all sentences with homographs as incongruent and try to read the sentences in both languages to make their decision. When the homographs were in English, this urge became even stronger, since the English reading was sometimes incongruent with the rest of the words in a Spanish sentence. In this situation the role of top-down expectations, which would help the participant in selecting a set of candidate responses, might be expected to increase. This demand characteristic of the task can help in explaining the pattern of effective connectivity which differentiated homograph from cognate processing.

Graphical models in Experiment 3 suggested a differentiation of reading routes for English and Spanish. Reading Spanish words relied more on a dorsal route, which was previously associated with sub-lexical rule-based processing. This was explained by the fact that orthography-to-phonology mapping for Spanish is more consistent, than it is for English. The sub-lexical route became activated, whenever participants read in Spanish, regardless of stimulus type. In Experiment 4 no feed forward projections was found in the homograph condition, only direct feedback activations from the IFG. This may be related to the fact that expectations are much stronger in the sentence reading context than in the context of single words. In the cognate condition of Experiment 4 both a direct projection from the temporo-occipital MTG to pars opercularis and an indirect projection from SMG to pars triangularis were found. This may be related to the fact that while most of the sentence was in Spanish, the final word was in English. Therefore, participants relied on both the lexical and the sub-lexical routes to complete the task. Interestingly the projection from SMG, an area thought to be involved in orthography-tophonology conversion went to pars triangularis, a part of the IFG, involved in speech production. In contrast, the direct projection from temporo-occipital MTG went to pars opercularis, which is considered to be important in semantic processing. This suggests that posterior temporo-occipital areas play a role in channeling relevant input to the correct processing locations in the prefrontal cortex.

Conclusion

Previous work investigating neural activity in the VWFA focused on single word reading. While this approach provides an initial model for studying reading processes, it fails to account for the complexity of interactions that exist between linguistic codes. Experiment 4 investigated the activity of the word reading system using a sentence congruence task and showed that while the VWFA is not affected by sentence level congruency, it interacts in important ways with other parts of the reading network. The findings of Experiment 4 demonstrated that a cognitive operation as sophisticated as reading relies at least as much on the top-down predictive activations, as on the incoming visual information.

Chapter 6: General Discussion

Recent neuroimaging literature has highlighted a number of functionally defined regions in the inferior temporal lobe thought to be specialized for processing different categories of visually presented objects. A face-selective region (Fusiform Face Area; e.g., Epstein & Kanwisher, 1998); an area sensitive to landscapes and spatial locations (Parahippocampal Place Area; e.g., Maguire et al., 2001); an area responding to human bodies and an area sensitive to tools (Extrastriate Body Area, Middle Temporal Gyrus Tool Area; e.g., Downing, et al., 2005) have been identified. Among these areas is the Visual Word Form Area, a part of the fusiform gyrus thought to be dedicated to processing written words (Cohen et al., 2000; 2002).

While oral language has a long history and relies on well developed brain mechanisms which have behavioral, neural and genetic parallels across species (Bolhuis, Okanoya, & Scharff, 2010); written language is a relatively new cultural invention. It emerges following extensive training and involves recycling of biologically older visual systems which can carry out fine-visual discriminations necessary for reading (Vinckier et al., 2007). The acquisition of literacy in childhood is related to key structural changes in the brain circuitry, including the appearance of functionally specialized areas for processing print (e.g., Maurer et al., 2006). Unfortunately, these ontogenic changes are almost impossible to dissociate from concurrent biological and social maturational processes (Carreiras, et al., 2009). In recent years, the investigation of the neural correlates of literacy has turned to studying adults in the hopes of mitigating the confounding effects of maturation (e.g., Dehaene et al., 2010). In this dissertation I studied 2 cohorts of fluent bilingual speakers in order to measure the biological consequences of acquiring literacy in two languages.

Relatively few functional imaging studies focused on the activity of the VWFA in bilingual speakers, and the majority of these have investigated languages that use distinct writing systems. This work suggested that the right VWFA homologue may be recruited when reading in two distinct writing systems (e.g., Perfetti et al., 2007; Nelson et al., 2009). However, it was not clear whether this finding generalized beyond languages as distinct as English and Chinese. It was hypothesized that languages that are more visually similar may produce similar activation of the left VWFA. I chose to focus on the VWFA response to languages that use the same writing systems, but have different orthographies, such as Spanish and English.

In 4 experiments the functional characteristics of the VWFA were investigated using single word reading and sentence comprehension. In Experiments 1 and 2 neural activity in the VWFA for Spanish and English words was contrasted with random
checkerboard patterns. This comparison revealed overlapping sub-regions in the temporal occipital fusiform cortex which responded equally well to Spanish and English words. These common neural representations were thought to support a form of abstract orthographic processing, which generalized across languages. In addition, each language was characterized by the recruitment of distinct neural populations in the temporal occipital fusiform cortex. These neural populations were thought to process distinct orthographic features in each language, as well as early cues to language membership. The need for these distinct patches of cortex may disappear as proficiency in the two languages increases and orthographic processing becomes increasingly integrated. Highly proficient bilinguals may treat word in their two languages as if they represent the same word distribution. This was suggested by the regression analysis linking the degree of overlap in the activations for English and Spanish with participants' proficiency levels in each language.

Next, in Experiment 3, participants were presented with pairs of cognate and homograph items in English and Spanish. The VWFA's response to meaning was measured by comparing the degree of adaptation in this area as a function of stimulus type. It was found that while the VWFA showed neural adaptation to pairs of homographs, it did not show such adaptation to pairs of cognates. The different response of this area to cognates and homographs was taken as support for its sensitivity to meaning. To better understand the dynamics of interactions between the VWFA and other parts of the reading network, I used the IMaGES algorithm to estimate effective connectivity between areas thought to be part of the language network. While there were no differences across conditions with respect to feedback projections from brain areas implicated in processing semantics to the VWFA, I speculated that differences in the VWFA activation as a function of semantic overlap could arise as a result of more local interactions between anterior and posterior parts of the fusiform gyrus. Effective connectivity models also revealed that English targets engaged a direct ventral route from the VWFA to the frontal lobe and Spanish targets engaged an indirect dorsal route. This result indicated a qualitative difference in neural activity during reading in different languages and could be related to differential reliance of English and Spanish on sublexical orthographic and phonological processes. In addition, considering that prefrontal cortex has been implicated in semantic processing, a direct connection to this area could signal a fast and automatic access to meaning and would facilitate early semantic influences in visual word recognition. Overall, the graphical connectivity models were consistent with the existing dual-route theories and could help in developing a multi-level understanding of reading processes.

In Experiment 4, the processing in the VWFA was measured in the context of the whole reading network. In this experiment, participants read sentences in English and Spanish and were asked to judge whether a sentence was sematnically congruent or incongruent. When participants read sentences in Spanish, they recruited subcortical areas in the basal ganglia, thalamus and in the ventral opercular cortex in concert with prefrontal and temporal language regions. This pattern of activity seems to indicate increased motor planning and potential sub-vocal rehearsal during reading in a less fluent language. When participants read in English, which was their more fluent language, they activated the precuneal and cuneal cortexes. These areas are linked with motor planning and attentional switching. The VWFA was not affected by sentence-level congruency,

but it was modulated by the interaction of language and stimulus type. When Spanish sentences contained homographs in English this area became more active than when Spanish sentences contained cognates in English. Using graphical modeling, I found that this effect was due to increased top down projections from the prefrontal cortex directly to the VWFA and to adjacent areas. This increased top down monitoring was required for sorting out the different semantic representations activated by homographs in two languages.

Together the findings of the 4 experiments serve to expand the current understanding of the functions of the VWFA. They illustrate the great complexity of the VWFA's role in reading processes. First, the VWFA encodes words as lexical entries rather than sub-lexical morphemes or word forms. I've shown that this area is not only sensitive to the orthographic form of the words, but also to their meaning, a lexical-level characteristic. I proposed that the computation of meaning in the VWFA relies on its interactions with other parts of the language network, for example via a rapid feedback from adjacent anterior temporal areas. Second, during sentence reading activity in the VWFA is influenced by top down activation from the prefrontal cortex, showing that neural processing in this region is context-dependent. This implies that considering the VWFA activity during reading in isolation may be misleading. Third, the differences in the activity of the VWFA following acquisition of a second language suggest that the VWFA response may not be as homogeneous as was previously thought. Correlates of the reading system in the left and right hemispheres may be differentially sensitive to first and second language orthographies. Distinctive writing systems, such as the ones used by Chinese-English bilinguals, require bilateral activation of the VWFA, whereas writing

systems and orthographies that are visually similar, like those utilized in English and Spanish, rely on overlapping neural populations. These results show the flexibility of this region and its propensity to adapt to each person's unique language experience.

Generally speaking, our understanding of brain regions is greatly enhanced when we consider them in relationship to other parts of the same network. In 1999 McIntosh identified network analysis as an important direction in neuroscience:

> "If one is willing to accept that brain regions communicate with one another in the course of cognitive operations, then what one brain area does must be determined by what other areas connected to it are doing. When an area is more active in a cognitive task relative to a control task, that change must arise from neural interactions." (McIntosh, 1999, p.543).

Similarly, we should move beyond investigating task-induced differences in brain areas to a more comprehensive approach which examines neural systems and their dynamics. The present dissertation research illustrated that when task conditions and participant populations are selected, such that they fall outside the scope of mainstream research, useful characteristics may be discovered. More importantly, these characteristics can be fully accounted for by the patterns of interactions across brain areas.

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Appendix A: Supplementary Materials for Experiment 1

Language Experience questionnaire

LANGUAGE EXPERIENCE AND USE QUESTIONNAIRE

PLEASE ANSWER THE FOLLOWING QUESTIONS.

- 1. What is your native language?
- 2. What is your second language, if any?
- 3. How many years of foreign language education have you had (provide the number of years)?
- 4. In what language did you have the foreign language education (provide the language)?
- 5. What is your age?
- 6. What is your gender?
- 7. At what age (in years) did you start learning/were first exposed to your first language?
- 8. At what age (in years) did you become fluent in your first language?
- 9. At what age (in years) did you start learning/were first exposed to your second language?
- 10. At what age (in years) did you become fluent in your second language?
- 11. When you are speaking, what percent of the time do you speak in your first language (all the time = 100%, half the time = 50%, none of the time = 0%, or any other percent in-between)?
- 12. When you are speaking, what percent of the time do you speak your second language (all the time = 100%, half the time = 50%, none of the time = 0%, or any other percent in-between)?
- 13. When you are speaking, what percent of the time do you speak in both languages/engage in language mixing (all the time = 100%, half the time = 50%, none of the time = 0%, or any other percent in-between)?
- 14. What is the overall percent of the time you are exposed to your first language in a day (speaking, listening, reading, or writing) (all the time = 100%, half the time = 50%, none of the time = 0%, or any other percent in between)?
- 15. What is the overall percent of the time you are exposed to your second language in a day (speaking, listening, reading, writing) (all the time = 100%, half the time

= 50%, none of the time = 0%, or any other percent in between)?

- 16. Please rate you reading proficiency in your second language on a scale from 1 to 4 (1 poor; 2 fair; 3 good; 4 excellent).
- 17. Please rate you writing proficiency in your second language on a scale from 1 to 4 (1 poor; 2 fair; 3 good; 4 excellent).
- 18. Please rate you speaking proficiency in your second language on a scale from 1 to 4 (1 poor; 2 fair; 3 good; 4 excellent).
- 19. Please rate you reading proficiency in your first language on a scale from 1 to 4 (1 poor; 2 fair; 3 good; 4 excellent).
- 20. Please rate you writing proficiency in your first language on a scale from 1 to 4 (1 poor; 2 fair; 3 good; 4 excellent).
- 21. Please rate you speaking proficiency in your first language on a scale from 1 to 4 (1 poor; 2 fair; 3 good; 4 excellent).
- 22. Did your family immigrate to the United States? If yes, write down the year.
- 23. What language do you prefer to speak?
- 24. Who do you usually speak with in your first language?
- 25. Who do you usually speak with in your second language?

List of Stimuli for Experiment 1

English Word	Frequ ency	English Word	Frequ ency	Spanish Word	Translation	Freque ncy	Spanish Word	Translati on	Frequen cy
Afternoon	106	Equipment	167	Abanico	Fan	8.06	Castillo	Castle	33.52
Army	132	Evening	133	Abuela	Grandmother	35.8	Cierre	Zipper	22.17
Attack	105	Eye	122	Agujeta	String	0.04	Ciudad	City	393.74
Audience	115	Father	183	Ajedrez	Chess	8.46	Cobija	Blanket	2.23
Ball	110	Fell	92	Aletas	Wings	3.77	Compra	Purchase	36.94
Bed	127	Fight	98	Alfombra	Carpet	9.33	Cuenta	Account	305.54
Bill	143	Fire	187	Almohada	Pillow	7.1	Enfermera	Nurse	10.43
Blue	143	Floor	158	Altavoz	Speaker	1.05	Equipaje	Luggage	4.51
Book	193	Friend	133	Anaranjado	Orange	1.8	Escoba	Broom	3.86
Bridge	98	Game	123	Año	Year	590.21	Espalda	Back	44.12
Cattle	97	Green	116	Arbusto	Bush	1.27	Espina	Bone	4.86

Cent	158	Hair	148	Ardilla	Squirrel	1.88	Esquina	Corner	35.84
Clay	100	Hall	152	Armario	Cardboard	4.91	Farol	Streetlam	3.86
			-					p	
Club	145	Heart	173	Atasco	Blockage	1.18	Frijoles	Beans	4.64
Cold	171	Heat	97	Aula	Classroom	6.27	Grapadora	Stapler	
Color	141	Heavy	110	Balda	Shelf	0.04	Guantes	Glove	6.84
Committee	168	Hold	169	Ballena	Whale	3.59	Hecho	Made	418.98
Concern	98	Hospital	110	Baño	Bathroom	36.63	Helado	Ice-	9.2
		1						cream	
Conference	96	Hot	130	Basura	Garbage	14.99	Iglesia	Church	167.03
Constructio	95	Husband	131	Boleto	Ticket	3.77	Impuesto	Tax	20.26
n							1		
Corner	115	Income	109	Bombero	Firefighter	1.75	Izquierda	Left	65.33
Corps	109	Industry	171	Calabozo	Cell	6.62	Jugo	Juice	7.76
Council	103	Island	167	Esquina	Corner	0.35	Lata	Can	10.08
Cut	192	Jack	92	Cama	Bed	85.53	Limpieza	Cleaning	
Dark	185	Lead	129	Camarón	Shrimp	2.41	Llegada	Arrival	59.65
Date	103	Live	177	Canapé	Sofa	0.48	Lobo	Wolf	13.58
Deep	109	Machine	103	Carpa	Tent	5.39	Lucha	Fight	96.49
Degree	125	March	120	Cartel	Poster	11.04	Lugar	Place	433.09
Design	114	Market	155	Cartero	Postman	1.62	Manzana	Apple	8.15
Doctor	100	Material	174	Casa	House	544.78	Margarita	Daisv	80.94
Earth	150	Meeting	159	Casco	Helmet	12.58	Marido	Husband	62.04
Member	137	Sign	94	Martes	Tuesday	39.44	Pluma	Pen	12.05
Nation	139	Spring	127	Martillo	Hammer	7.93	Pulgada	Inch	0.92
Nature	191	Square	143	Mesita	Table	5.61	Oueso	Cheese	13.71
News	102	Station	105	Muier	Woman	304.31	Rastrillo	Rake	1.1
Note	127	Story	153	Mundo	World	543.72	Rava	Stripe	7.41
Officer	101	Straight	114	Navidad	Christmas	16.12	Rev	King	125.23
Oil	93	Student	131	Oleaie	Waves	2.63	Río	River	159.1
Pattern	113	Sun	112	Oscuro	Dark	32.82	Sala	Living-	76.5
	115	Sull	112	obearo	Duik	52.02	Sulu	Room	10.0
Person	175	Surface	200	Padre	Father	286 39	Sierra	Mountai	31.02
•••••	170		200	1 441 0	1 000101	200.07	Sielle	n	01.02
Poet	99	Talk	154	País	Country	641 61	Suelo	Floor	124 18
Pool	111	Tax	197	Pala	Shovel	4 4 3	Tarea	Homewo	44 78
1 001	111	1 uA	177	1 ulu	Shover	1.15	Tureu	rk	11.70
Radio	120	Temperatur	135	Panadero	Baker	2.94	Tiempo	Time	7384
ituuio	120	e	150	1 unuuero	Buiter	2.71	riempo	11110	750.1
Range	160	Test	119	Parabrisas	Windshield	2 32	Tiza	Chalk	32
River	165	Trial	134	Pato	Duck	5 65	Uvas	Grapes	5 78
Road	197	Volume	135	Peine	Comb	2.06	Velero	Sailboat	2.02
Scene	106	Walk	100	Penino	Cucumber	1 18	Vez	Time	882.91
Sea	95	Wall	160	Pérdida	Loss	42.68	Viernes	Friday	56
Season	105	Weight	91	Pista	Court	25.06	Vuelo	Flight	35 84
· / · / · · · · · · · · · · · · · · · ·	100	,, eigne	2 I	1 1010	Court	20.00	1 4010	1 115111	JJ.0-

Appendix B: Supplementary Materials for Experiment 2

Language Experience questionnaire

Adapted from Marian, Blumenfeld, & Kaushanskaya (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. Journal of Speech Language and Hearing Research, 50 (4), 940-967.

Language Experience and Tronciency Questionnane (LEAL-Q	Language	Experience and	Proficiency ()uestionnaire (LEAP-O
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Last Name	First Name	Today's Date	
Age	Date of Birth	Male 🗖	Female 🗖

 Please list all the langu 	ages you know in order o	f dominance:		
1	2	3	4	5

(2) Please list all the langu	ages you know in order o	f acquisition (your native	language first):	
1	2	3	4	5

(3) Please list what percentage of the time you are currently and on average exposed to each language. (Your percentages should add up to 100%):

List language here:							
List percentage here:							

(4) When choosing to read a text available in all your languages, in what percentage of cases would you choose to read it in each of your languages? Assume that the original was written in another language, which is unknown to you. Chur percentage chould add up to 10000.

(10ur percentages showa dad up to 100%).							
List language here							
List percentage here:							

(5) When choosing a language to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each language? Please report percent of total time.

(Your percentages should a	udd up to 100%):		
List language here			
List percentage here:			

(6) What percentage of the time (out of a total 100%) do you mix two of your languages?

Languages	and	and	and	other, please specify	other, please specify
List percentage here:					

(7) Please name the cultures with which you identify. On a scale from zero to ten, please rate the extent to which you identify with each culture. (Examples of possible cultures include US-American, Chinese, Jewish-Orthodox, etc):

Degree of identification	(click here for scale)				
List cultures here					

(8) How many years of formal education have you had? In the US_____, in another country_____; specify the country_____.

(9) In what language were y	you educated during t	he following years of	your life?		
Age	[4-7]	[8-11]	[12-15]	[16-19]	[20-23]
Language:					

(10) Date of immigration to the USA, if applicable ______.

If you have ever immigrated to another country, please provide country name and date of immigration here.

(11) Have you ever had a vision problem , hearing impairment , language disability , or learning disability ? (Check all applicable). If yes, please explain (including any corrections): _____.

Language:

This is my click here for options language.

All questions below refer to your knowledge of

(1) Age when you...:

	were first exposed to	could hold a simple conversation in	could read single words in	could read a newspaper in
Γ				

(2) Please list the number of years and months you spent in each language environment:

	Years	Months
A country where is spoken		
A family where is spoken		
A school where is spoken		
A working environment where is spoken		

(3) On a scale from zero to ten, please select your *level of <u>proficiency</u>* in speaking, understanding, reading and writing in from the drop-down menus: Speaking (click here for scale) Understanding spoken language (click here for scale)

opositing	(enter more not ocare)	Charactering operation ranguage	(circle incirc and octare)

(4) On a scale from zero to ten, please select how much the following factors contributed to you learning

Interacting with friends	(click here for scale)	Language tapes/self instruction	(click here for scale)
Interacting with family	(click here for scale)	Watching TV	(click here for scale)
Interacting in workplace	(click here for scale)	Listening to the radio	(click here for scale)
Formal classes	(click here for scale)	Reading	(click here for scale)

(5) Please rate to what extent you are currently exposed to in the following contexts:

Interacting with friends	(click here for scale)	Language tapes/self-instruction	(click here for scale)
Interacting with family	(click here for scale)	Watching TV	(click here for scale)
Interacting in workplace	(click here for scale)	Listening to radio/music	(click here for scale)
Formal classes	(click here for scale)	Reading	(click here for scale)

(6) In your perception, how much of a foreign accent do you have in ?

(click here for scale)

(click here for scale)

CURRICULUM VITAE Olga V. Boukrina June, 2012

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Research Interests

Cognitive Neuroscience:

fMRI data analysis using multivariate statistical classifiers and graphical modeling algorithms

Emphasis on visual processing of native and second language orthographies in the ventral occipito-temporal cortex

Interest in studying neural markers of language loss in heritage speakers and their utility for designing rehabilitation programs for stroke patients

Investigated structural differences in whole brain and hyppocampal volumes of insulinresistant and overweight adolescents.

Broad interest in academical and clinical research in cognitive neuroscience

Categorization:

Comparison in relational category learning, analogy and similarity

Language:

Effects of phonological and semantic similarity on native and second language processing Memory organization in fluent speakers of two-languages revealed by studies of polysemy

Education

Rutgers University, Newark, NJ Psychology Department Ph.D. Candidate

B. A. in Psychology, Italian Minor

Summa cum Laude

fall 2007 to fall 2012

Thesis Topic: Neural Networks Underlying Language Processing in Same Script Bilinguals: An Investigation of Functional Specificity in the Visual Word Form Area Thesis Committee Members: Dr. Mauricio Delgado (Chair), Dr. Jennifer Austin, Dr. Catherine Hanson, Dr. Stephen Hanson, Dr. Edwin Williams

Binghamton University, Binghamton, NY

Graduated May 2004

Honor's Thesis Title: *The Effects of Interlingual Phonological Overlap on Language Processing in Bilinguals* Thesis Committee Members: Dr. Cynthia Connine (Chair), Dr. Kenneth Kurtz, Dr. Richard Pastore

Publications

Marian, V., Blumenfeld, H.K., & Boukrina, O.V. (2008). Sensitivity to phonological overlap within and across languages. *Journal of Psycholinguistic Research*, *37*, 141-170.

Boukrina, O.V., & Marian, V. (2006). Asymmetry in impact of phonological overlap on native and non-native word recognition. *Journal of Social and Ecological Boundaries*, 2 38-67.

Boukrina, O.V., & Marian, V. (2006). Integrated phonological processing in bilinguals: Evidence from spoken word recognition. *Proceedings of the Twenty-Eighth Annual Conference of the Cognitive Science Society*, 101-106, Mahwah, NJ: Lawrence Erlbaum.

Kurtz, K.J., & Boukrina, O.V. (2004). Learning relational categories by comparison of paired examples. *Proceedings of the Twenty-Sixth Annual Conference of the Cognitive Science Society,* Chicago, IL.

Research in Progress

Austin, J., Boukrina, O.V., Marull, C. (In preparation). Behavioral and neural markers of language attrition in heritage speakers of Russian.

Boukrina, O.V., Hanson, S.J., & Hanson, C (Submitted). Modeling activation and effective connectivity of VWFA in same script bilinguals. *Human Brain Mapping*.

Hanson, S.J., Boukrina, O.V., & Hanson, C. (In preparation). Bilingual language (Spanish/English) acquisition predicts the amount of "Spanglish" in the visual word form area (VWFA).

Kurtz, K.J., Boukrina, O.V., Gentner, D. (In preparation). The role of side-by-side comparison in learning relational categories.

Conference Presentations

Boukrina, O.V., Hanson, S.J., & Hanson, C. (2011). *Neural correlates of first and second language processing*. Poster presented at the Society for Neuroscience conference, Washington, DC, USA.

Boukrina, O.V., Hanson, S.J., & Hanson, C. (2009). *Polysemy across two languages: Evidence from word recognition and picture naming.* Poster presented at Object Perception and Memory conference, Boston, USA.

Kurtz, K.J., & Boukrina, O.V. (2005). *Learning two classification schemes over a single domain*. Poster presented to the Twenty-Seventh Annual Meeting of the Cognitive Science Society, Stresa, Italy.

Internal Presentations

Boukrina, O.V. (May, 2012). *Visual word forms encoded by overlapping brain regions in Spanish-English bilinguals*. Poster presented at Rutgers University Brain Imaging Center (RUBIC) Inaugural Symposium, May 4, 2012.

Boukrina, O.V. (June 2011). On the nature of neural networks underlying first and second language processing. Dissertation Proposal Defense, Rutgers University, NJ.

Boukrina, O.V. (May 2010). *Neural correlates of bilingual language processing: The role of the Visual Word Form Area.* Talk given at the Annual End of the Year Talk Event, Rutgers University, NJ.

Boukrina, O.V. (May 2009). Language comprehension and production in bilinguals: A window into the organization of the bilingual memory system. Talk given at the Annual End of the Year Talk Event, Rutgers University, NJ.

Boukrina, O.V. (May 2008). *Integrated semantic processing in bilinguals: Evidence from spoken word recognition*. Talk given at the Annual End of the Year Talk Event, Rutgers University, NJ.

Boukrina, O.V., & Kurtz, K.J. (May, 2005). *The role of comparison in learning*. Talk given at the Weekly Cognitive Area lunch, Binghamton University, NY.

Boukrina, O.V. (May 2004). *The effects of interlingual phonological overlap on language processing in bilinguals*. Poster presented at the Annual Undergraduate Research Forum, Binghamton University, NY.

Research Experience

Rutgers University Mind and Brain Analysis research group	(director Dr.
Stephen José Hanson)	
Ph.D. Student fall 2	2007 to summer 2012
fMRI data analysis using multivariate statistical classifiers and Bayesian gr algorithms	aphical modeling
Emphasis on visual processing of native and second language orthog ventral occipito-temporal cortex	raphies in the
Programming experience in Python and R, Linux interfacing	
Trained as a Siemens 3T Trio fMRI operator	
Center for Brain Health NYU Medical Center (director Dr. And	ntonio Convit)
Volunteer for	all 2006-winter 2007
Investigated structural differences in whole brain and hyppocampal volume and overweight adolescents.	es of insulin-resistant
Bilingualism and Psycholinguistics Laboratory Northwestern	University,
Chicago (director Dr. Viorica Marian)	

Research Assistant *fall 2005-spring 2006* Investigated cognitive analytical processing, including reasoning by analogy in bilingual and monolingual speakers.

Used behavioral and eye-tracking evidence to describe the time course bilingual speakers Developed scientific writing skills	of lexical access in fluent
Learning and Representations in Cognition Laboratory, I University (director Dr. Kenneth Kurtz) Research Assistant <i>fall 2002-spring 2005</i> Participated in the development of lab projects on the role of side-by-s relational category learning, category based similarity, learning multip over a single domain, and reasoning by analogy	Binghamton ide comparison in le classification schemes
Laboratory Manager Training and supervision of the Research Assistants in the lab Participating in lab research Running weekly lab meetings Performing administrative duties in the lab	fall 200-spring 2003
Teaching Experience	
Part-Time Lecturer, <i>Rutgers University</i> , <i>NJ</i> PSYC 432: History and Modern Viewpoints in Psychology Developed and taught an advanced elective course	winter 2011 winter 2012
Part-Time Lecturer, Rutgers University, NJ PSYC 330: Psychology of Learning Developed and taught an advanced elective course summer 2011	summer 2008 summer 2010
Graduate Teaching Assistant , <i>Rutgers University</i> , <i>NJ</i> PSYC 302: Experimental methods in cognitive and behavior Taught a lab section consisting of 30 students Graded laboratory assignments and quizzes	spring 2009 ral sciences spring 2010
Graduate Teaching Assistant , <i>Rutgers University</i> , <i>NJ</i> PSYC 301: Laboratory in Statistical Methods Taught a lab section consisting of 30 students	fall 2008 fall 2009
Graded laboratory assignments and quizzes	fall-spring 2011
Graduate Teaching Assistant , <i>Binghamton University</i> , <i>NY</i> PSYC 359: Laboratory in Cognitive Psychology Taught a lab section consisting of 25 students Graded papers and assignments Determined students' final grade for the course	spring 2005
PSYC 239: Multicultural Psychology Facilitated teaching a classroom of 450 students Developed and evaluated weekly mini-tests	fall 2004
Undergraduate Teaching Assistant, Binghamton University PSYC 356: Learning Attended weekly class meetings Helped grade tests and final exam	v, NY spring 2004
RUSS 108: Intermediate Russian II	spring 2004

Taught a discussion session consisting of 9 students Helped develop classroom materials Administered periodic quizzes and exams

Academic Recognition

Recipient of the Norman Samuels Scholarship, Rutgers University (\$7,000) Cognitive Science Fellow, Northwestern University (\$18,000) H. B. Daly Memorial Award for Excellence in Undergraduate Research (\$100), BU Undergraduate Research grant (\$215), Binghamton University Member, Phi Eta Sigma National Honor Society Member, Phi Beta Kappa National Honor Society Member, The National Scholars Honor Society 1998 Novgorod Region Olympiad in Russian Language - 1st place Town of Borovichi Scholarship - Junior and senior years of High School

Professional Affiliations

Reviewer, 5th International Conference of the Cognitive Science Member and reviewer, Cognitive Science Society Member, Society for Neuroscience Member, Women in Cognitive Science