Modeling Activation and Effective Connectivity of VWFA in Same Script Bilinguals

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Abstract: Previous neuroimaging research revealed a small area in the inferior occipito-temporal cortex (VWFA), which seems to be involved in recognition of written words. The specialized response of the VWFA to words could result from repeated exposure to print in the course of functional fine-tuning of the brain. Research with bilingual speakers holds promise in helping to reveal response properties of the VWFA by assessing its sensitivity to language proficiency, word-form similarity, and meaning overlap across two languages. Using fMRI, we compared VWFA activity for cognate and homograph prime-target pairs in a group of fluent Spanish-English speakers. Cognates share form and meaning in two languages, while homographs only share form. Relative to baseline, the VWFA showed repetition suppression to pairs of homographs, but not to pairs of cognates, suggesting that this area is sensitive to word meaning. The different response to cognates and homographs was only observed when English was the prime language and Spanish was the target language. To help explain this result we compared patterns of effective connectivity between the VWFA and other parts of the reading network implicated in semantic and phonological processing. Our neural models showed that English targets engaged a direct ventral route from the VWFA to the frontal lobe and Spanish targets engaged an indirect dorsal route. Considering that frontal 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. *Hum Brain Mapp* 35:2543–2560, 2014. © 2013 Wiley Periodicals, Inc.

Key words: magnetic resonance imaging; reading; bilingualism; language; effective connectivity; language network

INTRODUCTION

Functional Specialization of the VWFA

Visual word recognition is a fundamental human capacity, which helps to encode and transmit knowledge. This capacity 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., Glezer et al., 2009; Vinckier et al., 2007], while others suggest that the VWFA also responds to pictures and may help to integrate word-forms with their meaning [e.g., Devlin et al., 2006; Price and Devlin, 2003, 2004]. Much of this work has assessed monolingual activation of VWFA. However, a new direction of research with

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bilingual speakers [e.g., Nelson et al., 2009; Perfetti et al., 2007] may provide greater insight into neural processing in the VWFA by assessing its sensitivity to overlap of visual form and meaning across two languages. This approach represents a novel way to adjudicate between the two competing views on the function of this area. 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 conceptual dissimilarity between them, or (3) may store information about the language membership of each word. By carefully manipulating the stimuli such that they differ on only one of those dimensions, we can measure the degree of this area’s functional specialization for processing of visual word-forms. In addition, studying adult bilingual speakers can help to clarify how the VWFA is modulated by language experience.

VWFA in Bilinguals

Relatively few functional imaging studies have focused on the activity of the VWFA in bilingual speakers, and the majority of these have investigated languages that use distinct writing systems. In one investigation, Perfetti et al. [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 [Nelson et al., 2009]. Thus, it appears that the Chinese writing system engages the right hemisphere homologs of the VWFA regardless of language proficiency, but that the right hemisphere homolog is recruited for English when English is the second language [but see Chee et al., 1999]. Although this work suggests that the right VWFA homolog may be recruited when reading in two different languages, it is possible that this may be true only for languages as distinct as English and Chinese. Languages that are more visually similar may produce similar 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, such as Spanish and English (e.g., Jamal et al., 2011). Assuming that visually similar orthographies will recruit VWFA in similar ways, orthographic similarity can be used to determine the role that semantic (conceptual) information plays 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. 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 overlap.

Activation of the VWFA by Cognates and Homographs

Words that are similar in orthography (homographs) and those that are similar in both orthography and meaning (cognates) across two languages provide the opportunity to segregate the effects of orthographic and semantic processing on the activity of the VWFA. If the VWFA processes only visual word-forms, 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 and 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 et al., 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.

Until recently, it has been widely accepted that the VWFA is functionally specialized for processing visual word forms. However, there is now evidence that neural activity in this area may be modulated by word meaning as well [e.g., Devlin et al., 2006] and that the VWFA activation during reading is correlated with the activation of left-lateralized areas associated with semantic processing [e.g., Vigneau et al., 2005]. In addition, an ERP study showed that processing of semantic information begins during early stages of reading, before neural activation has had time to reach anterior temporal and prefrontal regions [Penolazzi et al., 2007]. Thus, 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. 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 across two languages. In our study, we tested this hypothesis by presenting a group of Spanish–English bilinguals with pairs of cognates (e.g., Eng. *artist* - Sp. *artista*) and homographs (e.g., Eng. *pie* - Sp. *pie* [foot]) in the context of a masked priming paradigm. Neural activity observed during presentation of cognate pairs and homograph pairs was then contrasted with neural activity during

presentation of unrelated Spanish–English word pairs. A decrease, or neural adaptation, in activity during the conditions of interest (cognates or homographs) relative to baseline (unrelated pairs), if found, was taken as evidence of purely orthographic processing in this area.

Modulation of the VWFA Activity by Reading Proficiency

The idea that accumulating experience in reading drives the word-form response in the VWFA is at the core of the current understanding of its function. This idea is supported by developmental evidence from studies using electrophysiological recordings and functional imaging. For example, 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 is a negative deflection from baseline often linked to the activity in the VWFA [e.g., Maurer et al., 2005]. Moreover, insufficient or atypical activity of the VWFA was found in children with reading disabilities [Helenius et al., 1999; Paulesu et al., 2001; Salmelin et al., 1996; Shaywitz et al., 2002, 2004; Simos et al., 2000; 2002]. Together, these findings point to the increased tuning of the VWFA response to written words with 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 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 discussion]. 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.

Studying the effects of language proficiency in bilinguals on activity in the VWFA can help to disambiguate the influence of maturational shifts from reading ability. Bilingual participants often differ in their reading proficiency across two languages. These differences in proficiency stem from later acquisition of a second language and from different amounts of exposure and use of each language due to the influence of a predominantly monolingual environment. As a result, lexical representations in one language accumulate less practice and may be accessed slower than their more frequently used counterparts in the other language. Overtime, such pattern of language use produces relatively weaker links between phonology, orthography, and semantics in the less-dominant language [see Gollan et al., 2008 for an overview of the “weaker links” hypothesis]. In behavioral studies, differences in history of language use have been shown to contribute to bilinguals' asymmetry in word recognition across languages. Specifically, while visually presented prime words in the more-proficient language influence recognition of targets in the less-proficient language, the reverse effect is

often not observed or may be smaller in magnitude (e.g., Altarriba, 1992; Fox, 1996; Gollan et al., 1997; Keatly et al., 1994; Kroll and Sholl, 1992; Silverberg and Samuel, 2004; see also Van Hell and Dijkstra, 2002 for similar effects in trilinguals). Whether asymmetry in the speed of primed word recognition is correlated with divergent activation patterns in the VWFA 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 by addressing the degree of its amenability to reading experience.

The behavioral asymmetry in crosslinguistic influences during bilingual word recognition has been accounted for by the relatively slower processing of the primes in the nondominant language as compared to the targets in the dominant language [Gollan et al., 1997]. This may stem from (1) slower recognition of orthographic properties in the former language due to the lower overall visual exposure; (2) slower phonological recoding due to less frequent production in the nondominant language; or (3) later semantic access resulting from weaker links between orthography and the conceptual system. For languages such as Spanish and English, which share their writing systems, slower processing of words in the less-proficient language is unlikely to stem solely from differences in exposure to printed words in one of these languages, especially considering that ~15,000 English words share orthography with their Spanish counterparts [Nash, 1997]. Although orthography may be an important contributor, the effects of bilingual asymmetry in visual word recognition for same script languages are at least in part due to differences in the speed of semantic access and of phonological recoding from print. Moreover, these differences in behavioral priming effects likely originate from divergent patterns of activity across a network of brain areas thought to support orthographic, phonological, and semantic processing.

To discover how the VWFA is modulated by language proficiency we examined its activity in isolation and also as part of a reading network [see Bolger et al., 2005; Fiez and Petersen, 1998]. To this end we recruited a group of Spanish–English bilinguals with different levels of proficiency across their two languages. We predicted that the patterns of the VWFA activity would differ between conditions when priming direction was from the more-proficient language into the less proficient language (English–Spanish) than then reverse. It was hypothesized that these differences would arise from the interaction of visual input channeled from the occipital cortex and top-down semantic and phonological input from the frontal, temporal, and parietal regions. In line with this argument, 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 and superior temporal gyri. Similarly, Cornelissen et al. [2009] observed simultaneous peaks of MEG-recorded activity in the inferior frontal and the left middle fusiform gyri.

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

	Native language	Second language	Language preference	AFE Spanish	AFE English	AAF Spanish	AAF English	DTE Spanish (%)	DTE English (%)	DTU Spanish (%)	DTU English (%)	DTU Mix (%)	TRP Spanish (%)	TRP English (%)	NT
1	Spanish/English	Spanish/English	Spanish/English	At birth	At birth	2	2	40	60	35	65	50	100	100	
2	Spanish	English	Spanish/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
4	Spanish	English	English	At birth	11	4	14	20	80	15	85	3	100	100	23
5	English	Spanish	Spanish/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
9	Spanish	English	Spanish/English	At birth	5	2	6	25	75	50	50	25	100	92	18
10	Spanish	English	Spanish/English	At birth	4	2.5	5	20	95	20	80	15	100	75	14
11	Spanish	English	Spanish/English	At birth	4	2	21	70	30	60	40	0	100	100	22

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.

In the present study, we extended previous findings by conducting an effective connectivity analysis, which measures the influence that one neural region, exerts on another and reveals the underlying causal structure of network activity [Friston and Büchel, 2003]. It was predicted that processing in the more-proficient language would be associated with faster access to areas associated with semantic processing and more efficient use of regions associated with phonological recoding. A novel Bayesian search algorithm called IMaGES [Scheines et al., 1998; Ramsey et al., 2010, 2011] was applied to neural activation timeseries extracted 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 and Poeppel, 2004; Jobard et al., 2003; and in orthography-to-phonology conversion, Graves et al., 2010]; left Heschl's gyrus [HG; thought to store acoustic-phonemic speech codes, Hickok and Poeppel, 2004]; left angular gyrus [AG; linked with orthography-to-phonology conversion, 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 and 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]. We also included the right homolog of the VWFA, because some researchers have found it to contribute to reading in bilingual speakers [e.g., Nelson et al., 2009; Perfetti et al., 2007].

We combined evidence from localization methods, expected to reveal 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 variations in the pattern of interactions between brain areas. Our first goal was to determine the role that the VWFA plays in reading by assessing the degree of its sensitivity to semantic similarity between word forms in two languages. And the second goal was to test whether the VWFA is modulated by language proficiency by measuring the neural processing in this area in the context of its interactions with other parts of the reading network.

MATERIALS AND METHODS

Participants

Eleven normal adult participants were recruited with flyers posted on New York University campus (9 women, 3 men, mean age = 24.08 years, SD = 6.43). All participants had normal or corrected-to-normal vision and were judged as 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 I. Participants were treated in compliance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and the standards established by the New York University Human Subjects Committee. They received monetary compensation for taking part in the study.

TABLE II. Average frequency and length measures and their standard deviations for English and Spanish prime-target word pairs

Pair type	Frequency		Length	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Cognates				
English word	40.5	35.17	5.06	0.83
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
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

Frequency measures for English were obtained from Kucera and Francis [1967]. Frequency measures for Spanish were obtained from Davis [2006]. Frequency measures represent instances per million and length measures represent number of letters.

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)]. Homograph and cognate pairs differed by no more than three letters across languages [e.g., *success-suceso* (event)] and most of the pairs differed by a single letter [e.g., *tomato-tomate*; *tirade-tirada* (a throw)]; 7 of the cognate pairs and 8 of the homograph pairs had identical orthography. This ensured that the pairs were sufficiently similar in their orthography to produce the expected neural adaptation effect in the VWFA. In addition, we 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 stimulus was designated 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 [Davies, 2002; Kucera and Francis, 1967]. Frequency and length measures are provided in Table II. In addition to the word stimuli, 90 readable nonwords and 90 consonant strings were created for use in a word/nonword decision task. The nonwords 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.

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 nonword. 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 et al., 2007]. We verified that none of the participants spontaneously became aware of the primes through an informal interview conducted after the scan. Therefore, any behavioral or neural differences between conditions, if observed, would not be attributable to strategic processing.

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 Fig. 1). 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

Figure 1.

Crosslanguage 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.

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 nonwords and consonant strings, and required a “nonword” response. Participants’ reaction times and accuracy during the word/nonword decision period, as well as their blood-oxygen level dependent brain activity were recorded.

fMRI 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 × 64, FOV = 192 mm). Thirty-six contiguous oblique axial slices (3 × 3 × 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 × 256, 176 1-mm sagittal slices).

fMRI Localization Analysis

Image preprocessing and data analysis were performed using FSL 4.1 software (FMRB’s Software Library, <http://www.fmrib.ox.ac.uk/fsl/>). The first 8 s of each scanning session contained instructions and were not used for

analyses. 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 et al., 2002]]; and smoothed using a Gaussian kernel of FWHM 8 mm. A slice-timing correction for interleaved slice-recording was applied. The hemodynamic response function was modeled using a Gamma function (phase = 0 s, SD = 3 s, M 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].

A three-level statistical analysis approach was used 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 (Gaussianized 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 $P = 0.05$. 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 et al., 2003]. Group-level z (Gaussianized T/F) statistic images were thresholded using clusters determined by $z > 1.96$ and a (corrected) cluster significance threshold of $P = 0.05$ [Worsley, 2001].

IMaGES Graphical Analysis

Prompted by challenges to modeling of causal connections among brain regions, such as computational intractability of analyzing networks with more than 3 or 4 regions of interest (ROIs), Ramsey et al. developed a Bayesian search algorithm called IMaGES [(Independent Multiple sample Greedy Equivalence Search) Ramsey et al., 2010, 2011; Scheines et al., 1998]. 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 et al., 2010]. The algorithm starts with an empty graph for a set of ROIs. It then selects all possible models with one directed link and rates the models based on residuals computed in each timeseries 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 et al., 2011]. IMaGES offers an exploratory approach, in that it discovers the underlying

TABLE III. Reaction time and accuracy results during word/nonword decision task in Spanish and English broken down by the type of prime-target relationship

Prime-target pair type	Mean reaction time (ms)	Standard error (ms)	Mean accuracy (proportion correct)	Standard error
Spanish phase				
Repeated	772.89	46.10	0.97	0.01
Cognates	788.32	60.36	0.96	0.02
Translations	812.73	51.03	1.00	0.00
Homographs	1030.62	98.21	0.89	0.03
Cross-language unrelated	832.66	54.77	0.99	0.02
Within-language unrelated	1028.37	83.10	0.91	0.03
Consonants	696.15	26.04	0.99	0.01
Nonwords	1450.44	156.31	0.62	0.10
English Phase				
Repeated	738.59	41.39	0.99	0.01
Cognates	728.49	41.09	0.99	0.01
Translations	715.16	29.47	0.99	0.01
Homographs	731.43	35.03	0.99	0.01
Cross-language unrelated	719.20	32.36	0.98	0.01
Within-language unrelated	764.51	50.21	1.00	0.00
Consonants	705.27	26.06	0.99	0.01
Nonwrds	1186.77	120.91	0.84	0.06

causal structure, instead of testing a predetermined hypothetical model, as is the case with many other effective connectivity algorithms. 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 and recall of orientations [Ramsey et al., 2011].

In the course of the IMAGES analysis the same preprocessing was applied to the functional BOLD timeseries as during localization. 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]. Only the timeseries corresponding to the onset of the neural response to the target word were considered. 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 feed-forward connections, rather than receive them, we were able to find a single best fitting model per condition. Model fit was estimated using SEM parametric model with a regression optimizer.

RESULTS

Reaction Time

Reaction time data were analyzed separately for English and Spanish trials. For English, a 2×8 repeated-measures ANOVA with run (first, second) and prime-target pair type (cognates, translations, homographs, unrelated, repeated, within-language unrelated, consonants, nonwords) as within-subjects variables showed a main effect of prime-target pair type ($F_1(7,42) = 19.28$, $P < 0.001$, partial $\eta^2 = 0.66$; item analysis: $F_2(7, 164) = 78.76$, $P < 0.001$, partial $\eta^2 = 0.77$). 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, $t_1(11) = 1.87$, $P = 0.088$. In addition, participants recognized nonwords more slowly than all other stimuli (all P 's < 0.005).

For Spanish, a 2×8 repeated-measures ANOVA with run and prime-target pair type as within-subjects variables showed a main effect of prime-target pair type ($F_1(7,42) = 9.86$, $P < 0.001$, partial $\eta^2 = 0.62$; $F_2(7, 164) = 49.99$, $P < 0.001$, partial $\eta^2 = 0.68$). 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 ($t_1(10) = -2.81$, $P < 0.05$; $t_2(28) = 1.76$, $P = 0.09$) and for the within-language unrelated control condition ($t_1(10) = -3.88$, $P < 0.005$; $t_2(28) = 2.20$, $P < 0.05$). See Table III for mean reaction times per condition. Relative to the within-language unrelated control condition, reaction time advantage was found for repeated prime-target pairs ($t_1(10) = 3.81$, $P < 0.005$; $t_2(28) = 3.37$, $P < 0.005$), cognates ($t_1(10) = 5.80$, $P < 0.001$; $t_2(28) = 2.87$, $P < 0.01$), and translations ($t_1(10) = 4.29$, $P < 0.005$; $t_2(28) = 2.62$, $P < 0.05$). In addition, relative to homographs faster reaction times were found for repeated prime-target pairs ($t_1(10) = 3.12$, $P < 0.05$; $t_2(28) = 2.87$, $P < 0.01$), cognates ($t_1(10) = 3.49$, $P < 0.01$; $t_2(28) = 2.28$,

$P < 0.05$), and translations ($t_1(10) = 3.86$, $P < .005$; $t_2(28) = 2.62$, $P < 0.05$). The word stimuli and consonant strings were recognized faster than the nonword stimuli (all P 's < 0.005).

Accuracy

Accuracy data were analyzed separately for English and Spanish. The data are provided as proportion correct. For English, a 2×8 repeated-measures ANOVA with run and prime-target pair type as within-subjects variables showed a main effect of prime-target pair type ($F_1(7,42) = 7.62$, $P < 0.001$, partial $\eta^2 = 0.56$; $F_2(7, 164) = 25.73$, $P < 0.001$, partial $\eta^2 = 0.52$) and a significant interaction between prime-target pair type and run ($F_1(7,42) = 2.67$, $P < 0.05$, partial $\eta^2 = 0.31$; $F_2(7,164) = 3.88$, $P < 0.005$, partial $\eta^2 = 0.14$). The interaction was investigated further with a series of paired-samples t -tests, which showed that nonwords were identified with lower accuracy during the first run. This effect was significant only in the item analysis ($t_2(43) = -3.34$, $P < 0.005$) 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 nonwords ($M = 0.86$, $SE = 0.05$) were identified with less accuracy than all other stimuli (all P 's < 0.05).

For Spanish, a 2×8 repeated-measures ANOVA with run and prime-target pair type as within-subjects variables showed a main effect of prime-target pair type ($F_1(7,42) = 17.65$, $P < 0.001$, partial $\eta^2 = 0.75$; $F_2(7,164) = 73.26$, $P < 0.001$, partial $\eta^2 = 0.76$) and a significant interaction between prime-target pair type and run ($F_1(7,42) = 3.30$, $P < 0.01$, partial $\eta^2 = 0.36$; $F_2(7, 164) = 2.20$, $P < 0.05$, partial $\eta^2 = 0.09$). 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 ($M = 0.96$, $SE = 0.02$) than during the second run ($M = 1$, $SE = 0$), $t_1(6) = -2.60$, $P < 0.05$; $t_2(43) = -3.03$, $P < 0.005$. In addition, in the item-analysis, significantly lower accuracy was found for nonwords during the first run ($M = 0.51$, $SE = 0.03$) as compared to nonwords during the second run ($M = 0.63$, $SE = 0.04$), $t_2(43) = -2.55$, $P < 0.05$. As consonant-strings and nonwords 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, $t_1(10) = -3.31$, $P < 0.01$; $t_2(28) = -2.38$, $P < 0.05$ (see Table III). Relative to the within-language unrelated control condition, greater accuracy was found for translations, $t_1(10) = 2.76$, $P < 0.05$; $t_2(28) = 2.47$, $P < 0.05$. In addition, relative to homographs, significantly greater accuracy was found for repeated prime-target pairs ($t_1(10) = 2.25$, $P < 0.05$; $t_2(28) = 1.99$, $P = 0.057$) and translations ($t_1(10) = 3.68$, $P < 0.005$; $t_2(28) = 2.84$, $P < 0.01$), and a marginal advantage was found for cognates ($t_1(10) = 1.98$, $P = 0.075$; $t_2(28) = 1.56$, $P = 0.13$). The word

stimuli and consonant strings were recognized more accurately than the non-word stimuli (all P 's < 0.005).

Activation Maps

During a word/nonword 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 IV). 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 ($t(10) = 2.31$, $P < 0.05$). 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: $t(10) = 2.50$, $P < 0.05$; left AG: $t(10) = 2.31$, $P < 0.05$; see Fig. 2). 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.

Repeated Spanish prime-target pairs produced activations in the left AG, 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 IV). 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 ($t(10) = 2.63$, $P < 0.05$), the left MTG ($t(10) = 2.67$, $P < 0.05$) and the left AG ($t(10) = 2.62$, $P < 0.05$) and no differences relative to baseline for the English repeated condition (see Fig. 3).

During a word/nonword 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 IV). 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 ($t(10) = 2.60$, $P < 0.05$). Similarly, timeseries of activation extracted from the right hippocampus cluster

TABLE IV. Local maxima of neural activation during primed word recognition in English and Spanish

Harvard-Oxford cortical structural atlas label	Z-statistic	x	y	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

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.

Group-level Z (Gaussianised T/F) statistic images were thresholded using clusters determined by $Z > 1.96$ and a (corrected) cluster significance threshold of $P = 0.05$.

(with peak coordinates $x = 30$, $y = -38$, $z = -8$) showed significantly lower parameter estimates for translations relative to unrelated pairs ($t(10) = 2.51$, $P < 0.05$). No such deactivation was observed for cognates or homographs (see Fig. 4).

IMaGES Graphs

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 AG in the parietal lobe (see Fig. 5). When participants were shown English targets, a

Figure 2.

Relative signal strength during processing of Spanish targets, which were primed by their English cognates, translations, or homographs. Neural activity in each condition was compared to the crosslanguage unrelated prime-target baseline. Here and in all subsequent figures * $P < 0.05$.

direct connection to the inferior frontal gyrus was observed, and when they were shown Spanish targets, the inferior frontal gyrus was accessed via the AG. To

Figure 3.

Relative signal strength during processing of Spanish and English targets, primed by their identity primes. Neural activity in each condition was compared to the within-language unrelated prime-target baseline.

Figure 4.

Relative signal strength during processing of English targets, which were primed with their Spanish cognates, translations, or homographs. Neural activity in each condition was compared to the crosslanguage unrelated prime-target baseline.

determine if reliance on the AG was related to participants' proficiency levels in Spanish, a Spearman rank correlation analysis, which is resistant to outliers, was conducted between measures of proficiency and individual connection strengths in the cognate and homograph conditions with the Spanish target. In the homograph condition, we found a significant positive correlation of connection strength with self-reported age of acquired fluency in English ($\rho = 0.65$, $P < 0.05$) and a negative correlation with self-reported daily total use of mixed Spanish/English discourse ($\rho = 0.64$, $P < 0.05$; see Fig. 6).

No differences were found across conditions for the connections from the VWFA. The VWFA always projected to the TP and the right VWFA. However, we 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.

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, even when one of the languages is irrelevant to the task [e.g., Dijkstra et al., 1999; Duyck, 2005; Jared and Kroll, 2001; Van Heuven et al., 1998]. For example, bilinguals read cognates presented in one language (e.g., Dutch-English: *sport-sport*; Dutch-German: *dier-Tier*) faster, than control words [Dijkstra et al., 1999]. Such processing advantage has been

generally explained by simultaneous and nonselective language access. Presentation of a word in one language activates orthographic, phonological, and semantic representations in both languages [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.

In this study, 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, as 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, word recognition will be hindered in bilinguals. This type of impaired processing is often called the *homograph interference effect* [Silverberg and Samuel, 2004; Von Studnitz and Green, 2002; but see Van Wijnendaele and Brysbaert, 2002].

We also found stronger priming effects from English to Spanish, than from Spanish to English. This effect replicates previous word-recognition studies in which greater crosslinguistic influence was shown for one language of a bilingual [e.g., Altarriba, 1992; Fox, 1996; Keatly et al., 1994; Kroll and Sholl, 1992]. This effect is often thought to be related to proficiency. For our group of bilinguals, average reaction time was 100–200 ms slower in Spanish than in English (see Table III), and their accuracy at detecting false words was lower for Spanish than for English, suggesting that our bilinguals processed words more efficiently in English. The majority of behavioral literature on bilingualism documents a similar asymmetry, where the bilingual's dominant, or the more proficient, language reliably affects processing in the nondominant, or less proficient, language; whereas the reverse is not generally found [e.g., Chen et al., 1997; Silverberg and Samuel, 2004; Van Hell and Dijkstra, 2002; Weber and 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.

Activation Maps

Neuroimaging results showed that presentation of Spanish words, primed with English homographs, produced a

Figure 5.

Analyses of effective connectivity between areas implicated in language processing using IMaGES [Ramsey et al., 2010]. 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.

decrease in the VWFA activity relative to the control condition. This finding could be explained by neural adaptation [Grill-Spector and 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 [Nakamura et al., 2010]. Importantly, the English-Spanish cognate pairs did not produce the same neural adaptation 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 notion of functional specialization of the VWFA for processing visual 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. If both cognates (e.g., error-error) and homographs (e.g., pie-pie) were processed by the VWFA as pairs of identical visual word-forms, an adaptation response should have been observed for all such stimuli. Our results, however, do not support this hypothesis. Finding the effect of semantic congruence/incongruence in the VWFA means that this area must either process 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 prelexical function of this

Figure 6.

Spearman rank correlation between the strength of connections to the angular gyrus (obtained from the graphical effective connectivity analysis) and two self-report measures of linguistic competence.

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 et al., 2001]. However, one recent report by Glezer et al. [2009] found no differences in processing pairs of semantically related words (*boat-ship*) and pairs of unrelated words in the VWFA. Thus, the lack of word-form adaptation in this area's activity to pairs of cognates may be mediated by the special status of cognates with overlapping representations at the orthographic and semantic [De Groot and Nas, 1991] levels, supporting the notion that the VWFA is an integration area. It also underscores the important status of cognates in the bilingual lexicon. Cognates may be used as important anchors that establish commonality between two lexicons during second-language acquisition.

In monolingual English speakers, VWFA activity has also 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 nonidentical

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 et al., 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. As such, it provides strong evidence of the VWFA's sensitivity to semantic information.

Similarly to our behavioral findings, neural priming effects for homographs were only observed in one direction of priming: we 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 and Stewart, 1994]; our results indicated that the VWFA deactivation 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 we consider patterns of effective connectivity across regions within the language network. Importantly, differences observed in the VWFA activity as a function of the language used for the prime indicate experience-based flexibility of this area.

In addition to VWFA, deactivations to the English-Spanish homograph pairs were observed in the left posterior middle temporal, angular, and inferior temporal gyri. Left middle temporal gyrus has been shown to support the conversion of orthographic representations into their corresponding phonology [Graves et al., 2010; Jobard et al., 2003; Sandak et al., 2004] and activity in the left inferior temporal gyrus is likely related to word-form retrieval. Support for this claim comes from work by Gaillard et al. [2006] who showed that an epilepsy patient, who underwent a resection of inferior temporal and fusiform gyri, exhibited letter-by-letter reading with longer latencies for longer words. Such a deficit implies that inferior temporal gyrus may contribute to the retrieval of whole words. In our study, English homographs of Spanish targets primed the retrieval of the target's orthographic and phonological forms and this could have produced a lower than usual amplitude of neural response in these areas.

Activity in the dorsal AG bordering with supramarginal gyrus [an area implicated in phonological processing, e.g., Abel et al., 2009; Jobard et al., 2003; Vigneau et al., 2006] has previously been linked with phonological and word-form retrieval [e.g., Hillis et al., 2005]. Decreased activity of the AG 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 play a role in rule-based orthography-to-phonology conversion. 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. In addition, activity in the AG has been identified as an important correlate of proficiency, a finding particularly relevant to our connectivity findings. For example, one study found that this area was modulated by the level of language proficiency in German–English bilinguals, who acquired English after the age of 6 [Wartenburger et al., 2003]. Activity in this area increased with higher proficiency. Mechelli et al. (2004) also found increases in gray matter density of this part of cortex in bilinguals, as compared to monolinguals. These structural volumetric increases were positively correlated with proficiency and negatively correlated with the age of second-language acquisition. These findings may indicate that this area supports second language processing, and becomes especially important when bilinguals begin to acquire second-language fluency.

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 and 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.

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, we 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., 2004]. 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 noncognate 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 I).

A second notable finding was that during word recognition in English, translation prime-target pairs showed neural deactivation of ventral temporal cortex, relative to the unrelated prime-target pairs. 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 have previously been associated with repetition priming and with skill learning, such as mirror-reading, [e.g., Poldrack and Gabrieli, 2001; Voss et al., 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 neuroimaging studies of reading reported correlations between activity in the fusiform gyrus (including the VWFA) and other parts of the language network in the frontal and temporal lobes [Mechelli et al., 2005; Vinckier et al., 2007], suggesting that no single brain area may be solely responsible for reading. Moreover, psycholinguistic models posit that there may be multiple processing mechanisms underlying lexical access. For example, the dual-route cascaded model [Coltheart et al., 1993, 2001] assumes both a direct look-up in the orthographic lexicon and an indirect orthography-to-phonology conversion. Similarly, the single-process connectionist model [Plaut et al., 1996; Seidenberg and McClelland, 1989] postulates that words can be read via a direct mapping between orthography and phonology, or via a mapping mediated by semantics. 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 and Dronkers, 2011]. In sum, our finding that reading words in first and second language engages different brain pathways rests on a solid foundation of past psycholinguistic and neuroimaging research.

We showed that AG mediated connections from the temporal lobe to the IFG whenever participants were reading

Spanish, but not English target words. To the extent that IFG is thought to be involved in semantic/syntactic processing [e.g., Hickok and 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 orthographic input (VWFA) and semantic output (IFG) channels. This connectivity pattern provides one possible way to account for the bilingual asymmetry in our primed lexical decision results. As Spanish words required additional processing in the AG their processing in the IFG 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 words, our participants showed both the homograph interference and cognate facilitation (e.g., Costa et al., 2000) effects. One caveat of this interpretation is that AG has also been implicated in semantic and pragmatic processing [e.g., Binder et al., 1997, 2005, 2009; Price, 2012; Price and Mechelli, 2005]. However, in studies showing this effect angular gyrus was localized to a more inferior part of the temporo-parietal cortex, whereas our angular gyrus ROI was located more dorsally in the area often activated by verbal-fluency tasks [Poline et al., 1996; Warburton et al., 1996].

Importantly, we show here that proficiency differences can modulate the processing mechanisms described above, potentially by inflating asymmetries in cross-linguistic influences. Our correlation analysis linked two self-report measures of language proficiency and use with the individual connection weights between temporal pole and AG (see Fig. 6). This is consistent with previous work, which linked patterns of functional connectivity of the AG with reading skill. For example, weaker functional connectivity between the IFG and AG, or between fusiform gyrus and AG has been found in adults with reading difficulties [Horwitz et al., 1998]. Dyslexics also show weaker connectivity of AG with temporal and occipital sites during word rhyming [Pugh et al., 2000] and weaker modulation of AG and supramarginal gyrus by fusiform gyrus and IFG have been found in children with dyslexia performing conflicting orthographic/phonological tasks [Cao et al., 2008]. Furthermore, decreases in white matter density, signaling decreased connectivity, and gray matter volumes in left inferior parietal regions have been found in adults and children with dyslexia [Eckert et al., 2005; Silani et al., 2005]. Our analyses indicated that increased age of acquired fluency in English was correlated with stronger connections to the AG during homograph recognition in Spanish. Our participants acquired Spanish as their first language and, therefore, the self-reported age of acquired fluency in English could be related to the length of

monolingual exposure to Spanish before the onset and acquisition of the second language. This is consistent with the studies that show a positive correlation between connections to the AG and reading skill. In addition, we found that increased mixing of the two languages in communicative contexts was negatively correlated with connection strength. Most of our participants were living in a predominantly monolingual English environment at the time of testing as indicated by the self-reported proportions of daily total exposure. Therefore, a pattern of language use showing increased mixing of the two languages is indicative of increased intrusions from the second language and potentially of first language attrition. The less participants mixed languages, the more they preserved the first language from attrition, and consequently the greater proficiency they had in that language (Spanish).

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 participant's language ability may contribute to the different effective connectivity patterns displayed by English and Spanish. Because of its more transparent mapping of orthography-to-phonology, Spanish may be more likely to engage the rule-based sublexical assembly [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 whole word reading. In sum, the patterns of effective connectivity obtained for reading English and Spanish targets seem to be related to participants' proficiency in each language and to the processing demands imposed by each language, independently of language ability.

Proficiency level has long been considered a major determinant of the patterns of brain activation in bilinguals, especially in tasks that target lexico-semantic processing [Perani and Abutalebi, 2005]. Differences in proficiency between first and second language have been shown to affect activity in ventral and lateral occipital cortex [greater activity for the less proficient language, Leonard et al., 2011], left temporal cortex [more for L1 and higher proficiency L2, Perani et al., 1998; Pratt et al., 2012], left prefrontal cortex [decreased activation with increased proficiency, Stein et al., 2009; Wartenburger et al., 2003], and areas linked with motor planning for articulation. For example, Meschyan and Hernandez [2006] examined neural activity during covert word reading in Spanish and English in a group of Spanish-English bilinguals, who were more proficient in their second language. When participants read Spanish words they activated supplementary motor area, putamen, and insula more, than they did when reading English words. These activations were interpreted as relating to more effortful articulatory

motor processing in Spanish. As proficiency level in both languages increases, the qualitative differences between first- and second-language neural processing disappear [Green, 2003]. An important contribution of our study to this body of work is in showing that even in the absence of activation differences there may be differences in functional dynamics between first and second language processing. For instance, our effective connectivity analyses showed that both English and Spanish recruited the AG; however, for Spanish this occurred early in the lexical access time-course, whereas English words were processed in the AG only after activation reached the IFG. Localization evidence alone would have not shown these important timecourse differences.

At the outset of our graphical analyses we predicted that neural activity in the VWFA would show qualitative differences in its interactions with parts of the language network when participants were reading in the more- and the less-proficient languages. Our predictions were confirmed as discussed above. In addition, we found an interesting departure in the connections of an area situated near the VWFA—the posterior MTG for cognates and homographs. The posterior MTG was previously implicated in reading [Paulesu et al., 2000], listening to a story [Abutalebi et al., 2007; Perani, et al., 1996, 1998] 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, while Graves et al. [2010] implicated it in orthography-to-phonology mapping. In our study, this area mediated the TP projections to the IFG and AG in all but one case, which was recognition of Spanish words primed with English homographs. Behaviorally, our participants were slower to perform this task, perhaps, because the activation of two competing semantic codes interfered with word recognition. As argued earlier, English primes were rapidly processed to the level of semantics and for Spanish targets the presentation time (3 s) was sufficient to allow for semantic coding. 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 or even inhibitory feedback to the posterior MTG, causing this area to decrease in activation. This interpretation is consistent with our localization results, which show a suppression response in MTG in this homograph condition.

CONCLUSION

Our graphical analysis revealed dissociable neural networks for Spanish and English in fluent bilingual speakers. Spanish words engaged the AG, 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 the role of inferior parietal cortex in proficiency [e.g., Mechelli et al., 2004] and provide a potential neural mechanism that could explain asymmetry in modulation of bilingual word recognition by the more- and the less-proficient language. 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, we show here that the VWFA is also 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 meaning buffered the VWFA against neural adaptation. These results support a role for the VWFA in integrating incoming orthographic information with meaning.

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