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Cortical activation during word processing in late bilinguals: Similarities and differences as revealed by functional magnetic resonance imaging

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Cortical activation during word processing in late bilinguals: Similarities and differences as revealed by functional magnetic resonance imaging

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Functional magnetic resonance imaging was used to compare cortical organization of the first (L1, Russian) and second (L2, English) languages. Six fluent Russian–English bilinguals who acquired their second language post-puberty were tested with words and nonwords presented either auditorily or visually. Results showed that both languages activated similar cortical networks, including the inferior frontal, middle frontal, superior temporal, middle temporal, angular, and supramarginal gyri. Within the inferior frontal gyrus (IFG), L2 activated a larger cortical volume than L1 during lexical and phonological processing. For both languages, the left IFG was more active than the right IFG during lexical processing. Within the left IFG, the distance between centers of activation associated with lexical processing of translation equivalents across languages was larger than the distance between centers of activation associated with lexical processing of different words in the same language. Results of phonological processing analyses revealed different centers of activation associated with the first versus the second language in the IFG, but not in the superior temporal gyrus (STG). These findings are discussed within the context of the current literature on cortical organization in bilinguals and suggest variation in bilingual cortical activation associated with lexical, phonological, and orthographic processing.

Bilingualism presents a unique setting for exploring fundamental questions about the cognitive architecture of language. With about 30 times as many languages in the world as there are countries (Romaine, 1995) and with at least half of the global population bilingual (Grosjean, 1982), bilingualism is the norm rather than the exception in the world (Harris & McGhee-Nelson, 1992). In the United States, the number of bilingual speakers is growing at a fast rate due to changes in ethnic, linguistic, and racial composition. The minority population (Spanish speaking in particular) is growing 12 times faster than the majority population, and the foreign-born population increased from 19.8 million to 30.5 million between 1990 and 2000, with 18% of American households speaking a language other than English (Daw, 2002). Understanding how the brain accommodates multiple languages at the same time can provide important insights into the cognitive and neural

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architecture of bilingual language processing, as well as have direct implications for this linguistically diverse and severely underserved segment of the population. The present research contributes to the understanding of cortical organization of language in bilinguals using functional neuroimaging, a technique that relies on the link between brain hemodynamics and mental operations (e.g., Belliveau et al., 1991; Belliveau et al., 1990; Ogawa, Lee, Kay, & Tank, 1990; Ogawa et al., 1992). While multiple studies have examined neural correlates of bilingualism in a global way, the objective of the present research was to distinguish among different aspects of bilingual language processing. In particular, cortical activation patterns were examined for lexical, phonological, and orthographic processing in the two languages.

Research on cortical organization in bilinguals has traditionally centered on the question of overlapping versus distinct representations of the two languages in the brain. On the one hand, a number of studies suggest that cortical representations of first and second languages are different. For example, selective disruption of L1 and L2 naming has been reported in cortical stimulation experiments, suggesting that at least some cortical regions associated with the two languages are separate (e.g., Ojemann & Whitaker, 1978). Selective language loss and/or differential recovery of languages in multilingual aphasic patients have also been interpreted as evidence for distinct cortical representations for each language (e.g., Gomez-Tortosa, Martin, Gaviria, Charbel, & Ausman, 1995; Nilipour & Ashayeri, 1989; Paradis, 1995; Paradis & Goldblum, 1989). Similarly, different event-related potential (ERP) patterns have been observed for bilingual and monolingual native-language processing, suggesting that acquisition of a second language modified neuroelectric responses in the native language (e.g., Donald, Meuter, & Ardal, 1986). Further support for differences in processing L1 and L2 comes from functional magnetic resonance imaging (fMRI) evidence that acquisition of Mandarin tones by American learners was associated with cortical reorganization (Wang, Sereno, Jongman, & Hirsch, 2003).

On the other hand, a number of studies have found evidence for overlapping cortical representations in bilinguals. For example, ERP patterns of Farsi–English bilinguals involved the same general cortical regions for both languages (Sarfarazi & Sedgwick, 1996). Similarly, overlapping regions of activation in the left inferior frontal gyrus were found in French–English bilinguals using positron emission tomography (PET) (Klein, Milner, Zatorre, Meyer, & Evans, 1995). Functional neuroimaging studies also reported overlapping regions of activation for both languages in frontal (Illes et al., 1999) as well as temporal and parietal lobes (Chee, Tan, & Thiel, 1999b).

The discrepancies among studies reporting distinct versus overlapping cortical regions associated with processing L1 and L2 have been attributed to differences in tasks and stimuli used in experimental methodology, and in participant language history (e.g., Abutalebi, Cappa, & Perani, 2001; Marian, in press; Vaid & Hull, 2001). Studies of cortical representation in bilinguals with different language histories suggest that age of L2 acquisition may account for some of the observed discrepancies. It appears that bilinguals who acquired both languages in parallel from early childhood show overlapping activations when processing their first and second languages (Chee et al., 1999b; Illes et al., 1999; Kim, Relkin, Lee, & Hirsch, 1997; Perani et al., 1998). In contrast, bilinguals who acquired a second language later in life activate somewhat distinct areas when processing L1 and L2 (Dehaene et al., 1997; Kim et al., 1997). For example, Kim et al. compared bilinguals who learned both languages in parallel from early childhood (early bilinguals) to bilinguals who acquired their second language later in life (late bilinguals) using a subvocal language production task. Functional neuroimaging revealed overlapping inferior frontal gyrus (IFG) and superior temporal gyrus (STG) regions of activation associated with L1 and L2 in early bilinguals. In late bilinguals, however, distinct centers of activation were associated with processing the two languages in the IFG, but not in the STG. Yet, age of L2 acquisition alone does not account for all variability observed in the bilingual cortical organization literature. Studies with late bilinguals have yielded mixed results, ranging from reports that the two languages are processed similarly (Chee et al., 1999b; Illes et al., 1999; Perani et al., 1998) to reports that the two languages are processed differently (Dehaene et al., 1997; Kim et al., 1997). Some of these differences could be explained by taking into account language proficiency (Abutalebi et al., 2001), since qualitatively different mental operations might be involved in processing languages of different proficiency levels. While most studies found that bilinguals with a less proficient L2 showed more extensive activation in L2 than in L1 (Hasegawa, Carpenter, & Just, 2002; Vingerhoets et al., 2003; Yetkin, Yetkin, Haughton, & Cox, 1996; but see Perani et al., 1996), bilinguals who were equally proficient in both languages consistently showed similar patterns of activation for both languages (Hernandez, Dapretto, Mazziotta,

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& Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Perani et al., 1998).

The present study tested only late bilinguals who acquired their second language post-puberty and who were highly proficient in both languages. Testing bilinguals who were proficient in their L1 and L2 minimized variability due to different proficiency levels. Moreover, based on previous research with early and late bilinguals, we hypothesized that if indeed there were cortical differences between L1/L2 patterns of activation, these differences would be more apparent in bilinguals who learned their second language later in life. The greater likelihood of evincing between-language differences rendered late bilinguals a suitable group for testing initial hypotheses about L1/L2 differences across types of language processing. Thus, by testing a bilingual group that was homogeneous in terms of age of acquisition and language proficiency, the focus of the present study was to examine bilingual cortical organization while differentiating among types of language processing, such as lexical, phonological, and orthographic. Specifically, the lexical level involves processing of word forms and their meanings, the phonological level involves processing of language-specific sound categories and sound combinations, and the orthographic level involves processing of language-specific letter symbols and letter combinations. In monolinguals, lexical, phonological, and orthographic inputs have been found to activate the same cortical language network, but were associated with somewhat different patterns of activation.

For lexical processing, neural correlates have often been studied by comparing activation patterns in the presence of lexical content (during processing of words) to activation patterns in the absence of lexical content (during processing of nonwords). While both words and nonwords have been shown to activate the left IFG during naming (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Warburton et al., 1996; for a review, see Indefrey & Levelt, 2000) and during auditory word recognition (Newman & Twieg, 2001; Xiao et al., 2005), only words have been found to consistently activate the left IFG during written-word recognition (e.g., Turkeltaub, Eden, Jones, & Zefifiro, 2002). For example, silent reading tasks activated the left IFG when input consisted of words, but not of nonwords (e.g., Mentzel et al., 2003). In general, the left IFG has been consistently associated with processing of lexical content, for instance in tasks involving semantic judgment (e.g., Binder et al., 1997), semantic comparison (e.g., Chee et al., 2000), semantic learning (e.g., Kapur et al., 1994; Wagner et al., 1998), and lexical retrieval (such as choosing a context-appropriate word from the mental lexicon, e.g., Raichle et al., 1994; Sharp et al., 2005). For example, Thompson-Schill, D'Esposito, Aguirre, and Farah (1997) showed that when given a noun, retrieving a corresponding verb involved IFG activation, but repeating the noun did not. Together, these findings suggest that the left IFG is reliably involved in lexical processing and that a close examination of this area is particularly likely to reveal fine-grained differences between L1 and L2, if such differences do in fact exist.

Not only is the neural language network influenced by lexical status, but it is also sensitive to modality of linguistic input. While auditory and visual language processing are part of the same neural network (Bitan et al., 2005; Booth et al., 2003), a number of studies suggest differences in patterns of activation associated with the two (Binder et al., 1994; Chee, O'Craven, Bergida, Rosen, & Savoy, 1999a; Fujimaki et al., 1999; Nobre, Allison, & McCarthy, 1994; Petersen, Fox, Snyder, & Raichle, 1990; Price & Giraud, 2001; Shaywitz et al., 1995a). For example, Shaywitz et al. (1995a) reported activation in bilateral inferior frontal, as well as in left posterior temporal and right cerebellar regions for monolingual language processing in the auditory modality, but not in the visual modality. Similarly, Booth et al. (2002) found that the superior temporal gyrus was activated by auditory processing of phonological word forms, while the fusiform gyrus was activated by visual processing of orthographic word forms. For phonological processing, results of monolingual studies vary from activation primarily in the IFG (Zatorre, Evans, Meyer, & Gjedde, 1992), to activation primarily in the STG (Demonet et al., 1992; Petersen, Fox, Posner, Mintun, & Raichle, 1989; Shaywitz et al., 1995a), to activation in both the IFG and the STG (Nixon, Lazarova, Hodinott-Hill, Gough, & Passingham, 2004; Paulesu, Frith, & Frackowiak, 1993).

Given that lexical, phonological, and orthographic processing are associated with distinct patterns of neural activation in monolinguals, an accurate account of bilingual cortical organization must also differentiate among different levels of language processing. To accomplish this, the present study manipulated the modality of linguistic input and the lexical status of stimuli by having bilingual participants listen to or read blocks of words or nonwords. Neural correlates of *lexical processing* were identified by isolating activation unique to processing words (excluding activation associated with nonword processing).

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Only activation that was shared across both the auditory and visual modalities of linguistic input was examined, to eliminate sensory-specific activation. Neural correlates of *phonological processing* in each language were identified by isolating activation common to auditory presentation of both words and nonwords (excluding activation in response to visual stimulus presentation). Similarly, neural correlates of *orthographic processing* in each language were identified by examining activation common to visual presentation of both words and nonwords (excluding activation in response to auditory stimulus presentation). It was predicted that while the same general language network would be activated during each level of processing, lexical processing would be more likely to consistently recruit frontal regions, while phonological processing would be more likely to also recruit superior temporal regions, and orthographic processing would be more likely to also recruit occipital regions. Moreover, for each level of processing, the two languages were predicted to show differences in patterns of activation. L1/L2 differences were expected in global hemispheric lateralization patterns, as well as in specific activation of established language areas such as IFG and STG.

For hemispheric lateralization, it is generally observed that the left hemisphere is dominant for language in most right-handed monolinguals (Frost, Binder, Springer, & Hammeke, 1999). There is less agreement on the issue of lateralization in bilinguals, particularly with respect to their second language. Albert and Obler (1978) argued for a larger role of the right hemisphere in L2 processing. However, evidence of greater right hemispheric involvement in L2 than in L1 is inconsistent. Although some neuroimaging studies do not find greater right hemisphere involvement in processing L2 (e.g., Chee et al., 1999b; Perani et al., 1998), recent results by Wang et al. (2003) indicate right hemisphere involvement in learning a second language, with lateralization patterns in bilinguals mediated by age of second-language acquisition (Vaid & Hall, 1991; Vaid & Hull, 2001). In the present study, specific comparisons of the volumes of activation within the left and the right IFG were performed. It was hypothesized that L2 would be more likely to recruit the right hemisphere than would L1, particularly areas homologous to the language areas in the left hemisphere.

Previous neuroimaging studies have found that areas involved in language processing include not only the classical language areas in the left perisylvian cortex such as the inferior frontal gyrus and the superior temporal gyrus (for a review, see Binder & Price, 2001), but also the middle and the inferior temporal gyri, insula, the striate/extrastriate cortex, the angular gyrus, the supramarginal gyrus, and the lateral frontal lobe (e.g., Binder et al., 1997; Friedman et al., 1998). However, the inferior frontal gyrus has been found to be especially sensitive to second-language learning (e.g., Abutalebi et al., 2000; Kim et al., 1997; Perani et al., 1996). Therefore, we were particularly interested in the size and location of activations within the inferior frontal gyrus. Given that Kim et al. (1997) reported greater L1/L2 differences in the IFG than in the STG during language production, we hypothesized that similar L1/L2 differences would also be observed during language comprehension, and that the distance between L1 and L2 centers of activation would be greater in the IFG than in the STG. In addition, we hypothesized that even within the same participants and for the same languages, the inferior frontal gyrus would show differences in activation across different types of language processing.

In summary, evidence from bilingual aphasia, cognitive experiments, and neuroimaging studies provide mixed accounts of whether cortical representation of a second language differs from that of a first language, particularly in bilinguals who acquired the second language later in life. The objectives of the present study were to examine cortical activation associated with processing L1 and L2 in a homogeneous group of late Russian–English bilinguals who were highly proficient in both languages. Specifically, lexical, phonological, and orthographic processing levels were considered, and neural representations of L1 and L2 were compared. Hemispheric organization, areas activated, volumes of activation, and central tendencies associated with processing the two languages were examined, and the following five predictions were made:

1. First- and second-language processing would rely on largely overlapping networks of cortical activation; however, some differences would be observed in lateralization patterns, as well as in size and center of activation, depending upon type of language processing.
2. Lexical, phonological, and orthographic processing would be associated with overlapping cortical networks. However, distinct activation patterns would be associated with the different types of processing. Namely, lexical processing would consistently recruit the IFG, while phonological processing would also recruit the

STG, and orthographic processing would also recruit the occipital cortex.
3. More extensive activation would be observed during second-language processing than during first-language processing.
4. The second language would be more likely to recruit right-hemisphere areas homologous to the classical language areas in the left-hemisphere.
5. L1/L2 differences would be greater in the IFG than in the STG.

METHOD

Participants

A total of 6 healthy Russian–English bilinguals (3 males and 3 females; mean age = 21 years, *SD* = 1.8) participated in this study. All participants were late learners of the second language (L2, English), their mean age at the time of arrival to the US was 14.8 years (*SD* =1.2), and their mean reported age at becoming proficient in the second language was 16.9 years (*SD* = 1.4). All participants were highly proficient in their second language at the time of study, as demonstrated by their high scores on standardized tests of English such as the TOEFL (Test of English as a Foreign Language) or the English portion of the SAT (Scholastic Aptitude test). All participants were students at premier American universities and were not enrolled in ESL classes. Participants continued using Russian on a daily basis with family and friends (mean daily Russian use reported = 3.5 hours, *SD* = 1.7), but used English in personal, academic, and professional settings for the remainder of the time, suggesting both maintenance of L1 and extensive use of L2. Of the 6 participants, 3 reported using English as the preferred language of communication, 1 reported using Russian as the preferred language of communication, and 2 reported no language preference. No participant was fluent in a language other than Russian and English.

Given the difficulty in selecting a homogeneous sample of bilingual speakers, our study is similar to other bilingual studies in that it reports results for a sample size of 6 or fewer participants (e.g., Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Leung, Gore, & Goldman-Rakic, 2002; Wang, Sereno, Jongman, & Hirsch, 2003). Moreover, fMRI studies with other special populations, such as children, also frequently report results for samples of similar size (e.g., Booth et al., 1999). The study's within-subject design and the fact that all comparisons were made within subjects increase the power of statistical analyses.

All participants were administered (a) a health-related screening questionnaire for being tested in a magnetic resonance scanner; (b) the Edinburgh Handedness Inventory assessing the laterality quotient (Oldfield, 1971); (c) a language history questionnaire assessing their experience with the two languages; and (d) an informed consent form, according to the Declaration of Helsinki. A physician examined participants' MRI scans for structural abnormalities; none were observed. All participants received monetary compensation for participation. Participants' demographic and language background is reported in Table 1.

Design and procedure

The study was conducted at the Functional Magnetic Resonance Imaging Laboratory of the Memorial Sloan–Kettering Cancer Center and was approved by the Institutional Review Board ethical committee. First- and second-language processing

TABLE 1
Participants' linguistic background information and laterality quotients

		Age[a]			*Scores on standardized tests*					
Participant	*Sex*	*Current*	*At arrival in US*	*At subjective fluency in English*	*TOEFL*	*SAT*	*Preferred language*	*Current Russian usage hrs/day*	*Other languages studied*	*Hand dominance*[b]
1	F	21.4	13.4	17.8	583		English	4	No	Right
2	M	20.3	14.0	14.0		670	No pref.	3	No	Right
3	M	23.4	14.1	16.3	597	490	Russian	4	Yes	Ambidextrous
4	F	21.8	16.4	18.0	633	580	English	0.6	Yes	Right
5	F	18.9	15.4	17.9	630	610	No pref.	4	Yes	Right
6	M	19.8	14.8	14.8	480	400	English	5	No	Right

[a]In years. [b]Handedness assessed by the Edinburgh Handedness Inventory (Oldfield, 1971).

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in late bilinguals was examined using a 2×2×2 factorial design, where all three factors—language (Russian and English), lexical status (words and nonwords), and modality of presentation (auditory and visual)—were varied within subjects. Thus, participants were tested in eight different conditions: Russian words auditory presentation, Russian words visual presentation, Russian nonwords auditory presentation, Russian nonwords visual presentation, English words auditory presentation, English words visual presentation, English nonwords auditory presentation, and English nonwords visual presentation. Stimuli were presented at a rate of 1 word (or nonword) per 2-s interval. Condition order for stimuli was randomized across participants. Each condition was presented during two epochs, using different words or nonwords for each. A multiple short-run technique was employed (Berman, Kim, Talati, & Hirsch, 1998; Gratton et al., 1997; Hirsch et al., 1995, 2000; Kim et al., 1997), consisting of 16 runs with each run lasting 144 s and including three parts—a baseline period (52 s), a testing period (40 s), and a final baseline period (52 s). This technique guards against false positives, while allowing for data acquisition across multiple conditions with minimal scanner time (288 s/condition × 8 conditions = 38.4 min). The relatively short duration of functional image acquisition has been found to yield reliable mapping of language areas in preoperative neurosurgery patients (Hirsch et al., 2000).

Participants were asked to listen to or silently read the words presented to them. Passive listening and reading tasks have been used successfully in prior neuroimaging studies of modality and presentation rate effects on language processing (e.g., Mechelli, Friston, & Price, 2000; Petersen et al., 1989). Passive listening tasks have been found to robustly activate the inferior frontal gyrus and the superior temporal gyrus and have been frequently used in neurosurgical planning (e.g., Hirsch et al., 2000) and in fMRI studies examining language processing in infants (e.g., Souweidane et al., 1999), as well as in previous bilingualism research (e.g., Rüschemeyer, Fiebach, Kempe, & Friederici, 2005). Listening and reading are the least complex linguistic tasks necessary to activate the areas of interest in this study, without also activating additional areas that would be involved in more complex linguistic tasks (such as rhyming, semantic judgment, articulatory planning, etc.). Moreover, both are receptive language tasks that, especially when associated with a relatively small sample size, are likely to result in least variation across participants, since no extraneous networks are involved. In the visual presentation trials, the baseline task consisted of participants fixating on a center cross displayed on a white screen (also used to help the participant maintain a stable head position), and the test task consisted of silently reading words and nonwords presented on the same screen. The visual stimuli were projected onto the screen from a videocassette recorder and subtended to a visual angle of approximately ±10 degrees. For visual stimuli, the font size and font color were constant between languages. In the auditory presentation trials, the exact same baseline task was used. During the rest phase, participants fixated on a center cross while no linguistic input was presented; during the test phase, participants heard words and nonwords in either the first or the second language. The auditory stimuli were played via tubular headphones. Upon completion of the study, participants were asked about the task performed, and all 6 bilinguals confirmed that they were indeed listening to or reading words in the two languages.

Stimuli

For each of the eight conditions, 40 words were selected, and 40 nonwords were created, with 20 words or nonwords in each of the two epochs. For words, only nouns were used, to avoid cross-linguistic differences in verb formation grammar. None of the words used were homophones (words that sound the same in both languages) or cognates (words that both sound and mean the same in both languages). The words presented in the Russian and English visual conditions were translation equivalents, as were the words presented in the Russian and English auditory conditions. Translation equivalents were used to ensure that if differences were observed across the two languages, these differences would be a result of processing different languages and would not be due to differences in content of the stimuli, such as the size of semantic network. Different nonwords were developed for each language following the phonotactic rules of each language in the auditory domain and by using the language-specific alphabets in the visual domain. Words and nonwords presented in the visual and auditory modalities were different in order to equate for novelty effects. In the visual trials, only words and nonwords that contained at least three letters unique to the alphabet of that language were chosen (for words and nonwords shorter than six letters, at least 50% of the letters were unique to the language). Russian and English words were matched for frequency across modalities. Word frequencies were computed using three different sources

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(Lonngren, 1993; Zasorina, 1977; Zeno, Ivens, Millard, & Duvvuri, 1995). The mean frequency of English words presented visually was 55 (median = 26, range = 1 to 366) per million, of Russian words presented visually 53 (median = 31, range = 1 to 466) per million, of English words presented auditorily 61 (median = 31, range = 2 to 417) per million, and of Russian words presented auditorily 62 (median = 30, range = 1 to 582) per million. In addition, the lengths of words and nonwords were matched across languages and across modalities of presentation. The mean length for English words presented visually was 5.5 letters (median = 5), for Russian words presented visually 5.4 letters (median = 5), for English words presented auditorily 5.5 letters (median = 5), and for Russian words presented auditorily 5.5 letters (median = 6). The mean length of English nonwords presented visually was 5.4 letters (median = 5), of Russian nonwords presented visually 5.6 letters (median = 5.5), of English nonwords presented auditorily 5.5 letters (median = 5), and of Russian nonwords presented auditorily 5.7 letters (median = 6).

The same speaker was used for recording both the Russian and the English stimuli. The speaker was selected from among 9 balanced Russian–English bilingual volunteers by a group of six judges (English monolinguals and Russian–English bilinguals). The judges rated a recorded speech sample of each speaker for absence of accent and for clarity of speech in both languages. The person with the highest score was selected to record the stimuli. The selected speaker was a fluent Russian–English bilingual female, who immigrated to the United States in early childhood, and did not have an accent in either language. The stimuli were recorded in a soundproof booth.

Image acquisition

A 1.5-tesla General Electric magnetic resonance scanner with a standard head coil capable of echo-planar imaging was used to obtain T2*-weighted images with a gradient echo pulse sequence (TE = 60 ms; TR = 4,000 ms; flip angle, 60°). The in-plane resolution was 1.5 mm by 1.5 mm. Slice thickness was 4.5 mm, and thus the size of a single volume element (voxel) was 1.5 × 1.5 × 4.5 mm. A total of 21 contiguous axial brain slices were obtained parallel to a standard reference line that intersected the superior edge of the anterior commissure and the inferior edge of the posterior commissure. This orientation allowed direct comparison of the acquired images with the Talairach and Tournoux (1988) *Human Brain Atlas* for identification of targeted brain structures. Conventional high-resolution T1-weighted images were also acquired at the same axial locations as the T2*-weighted images during each imaging session and served as a reference for subsequent anatomical labeling. A Gaussian spatial filter of half-height and half-width of 3.0 mm was applied. All acquired images were corrected for movement artifacts (Woods, Mazziotta, & Cherry, 1993) to allow direct spatial comparisons among all conditions using a common coordinate system for each participant. In order to preserve the highest resolution across participants, the acquired images were preserved and analyzed, rather than transformed onto normalized space. The comparison of centroids in a relatively small sample required that the topography of individual brains be preserved in order to obtain the highest resolution, with previous studies (e.g., Kim et al., 1997) showing that if this resolution is compromised, the effect in bilinguals is obscured. Instead, normalization to Talairach space (Talairach & Tournoux, 1988) was conducted manually for each participant in each condition. Output images of activation per condition were superimposed onto a 115×115-mm grid for each slice (n = 21) in each participant. Each slice was then matched to its corresponding axial Talairach image (i.e., z-plane). For each slice, distances in the x- and y-planes of the Talairach images were then compared to equivalent distances on the output grids, and the corresponding brain sites were labeled using the Talairach Atlas.

Data analyses

Signal intensities during stimulus presentation were compared to signal intensities during the two baseline stages that preceded and followed the stimuli across two epochs. Pixel-wise comparisons were performed, where a voxel was defined as active if the magnetic resonance signal during the period of stimulation was significantly different from both the initial and the recovery baseline stages in two epochs (Berman et al., 1998; Hirsch et al., 1995, 2000; Kim et al., 1997). The activated voxels were determined using independent t tests with 18 degrees of freedom that compared mean signal levels of activation during an on block (the test task block) to activation in the two flanking off blocks (the preceding and following baseline blocks); since each epoch consisted of 10 images, the two-way comparison resulted in 10 + 10 – 2 = 18 degrees of freedom. The criterion for significance was set at a false positive rate of $p < .0005$,

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which was corrected for the effects of multiple voxel-based comparisons over brain space and was replicated at this threshold within each subject. Thresholding was done on each component separately (e.g., on Russian word processing versus its baseline; Russian nonword processing versus its baseline, etc.) rather than comparing components directly. Comparing each component against its two baselines prior to comparing the two components directly is the most conservative way to analyze these data, so as to decrease the probability of Type I error.

Next, voxel-based analyses across two matching runs were performed, and center-of-activation coordinates across the two runs were identified for each participant. Replicating activations across two runs increases reliability of center-of-activation calculations: "The requirement that all statistical criteria be met on two separate runs serves to increase the probability that observed activity is due to a reliable event" (Hirsch et al., 2000, p. 713). Hirsch et al. (2000) point out that this "double-pass" method, where consistency between runs serves as a control, allows for shorter runs and acquisition of fewer volumes, offering statistical benefits otherwise reserved for scenarios where more volumes are acquired. The multiple short-run technique (Berman et al., 1998) allowed for collection of data across multiple conditions, while keeping scanner time to a minimum. The relatively short duration of functional image acquisition also increased the likelihood of obtaining data with mentally alert participants. Moreover, to establish that the reported activation was common across all subjects, additional analyses compared mean center-of-activation coordinates against individual data. Specifically, correlation and *t* test analyses compared mean *X*, *Y*, *Z* coordinates to center-of-activation coordinates for each participant. Correlation analyses yielded high Pearson *R* values, indicating that mean and individual coordinates varied systematically. Corresponding *t* tests yielded nonsignificant *t*-values ($p > .05$), indicating that individual coordinates did not deviate from mean center-of-activation values and fell within the same range (see Table 2).

Next, voxels that were activated in common across conditions and those that were unique to each condition were identified computationally. Planned comparisons between L1 and L2 were performed for lexical, phonological, and orthographic processing. Lexical processing was defined as voxels activated while processing words, but not activated while processing nonwords. For example, to determine the voxels involved during lexical processing of Russian, the sets of voxels that were active during Russian word processing but not active during processing of Russian nonwords were determined. Since words (and nonwords) were presented both auditorily and visually, only the overlapping areas for auditory and visual processing were considered when examining lexical processing, in order to eliminate the cortical systems associated with sensory processes (Hirsch, R-Moreno, & Kim, 2001; Price, Moore, Humphreys, Frackowiak, & Friston, 1996). Since theories of reading suggest that orthographic processing may automatically involve phonological processing, and since the existence of a direct route from orthography to lexicon (bypassing phonology) remains debated, attributing activation to orthographic and not phonological processing is difficult if only visual word recognition is tested. However, if word recognition is also tested in the auditory modality, it becomes possible to separate activation that overlaps across modalities from activation that is unique to each modality. Psycholinguistic studies suggest that a single

TABLE 2
Between-subject consistency in activated brain regions, as indicated by Pearson correlations and *t* tests between individual *X, Y, Z* coordinates and group means

	X		*Y*		*Z*		
Participant	*R*	*t*	*R*	*t*	*R*	*t*	*Mean R*
1	.99	0.05 ($p > .1$)	.69	1.70 ($p > .1$)	.57	0.50 ($p > .1$)	.75
2	1.00	0.08 ($p > .1$)	.78	1.09 ($p > .1$)	.32	1.19 ($p > .1$)	.70
3	1.00	0.22 ($p > .1$)	.32	1.78 ($p > .1$)	.46	2.23 ($p < .1$)	.59
4	.99	0.12 ($p > .1$)	.74	1.21 ($p > .1$)	.76	0.69 ($p > .1$)	.83
5	.99	0.07 ($p > .1$)	.74	0.91 ($p > .1$)	.49	0.06 ($p > .1$)	.74
6	1.00	0.14 ($p > .1$)	.67	0.22 ($p > .1$)	.80	1.10 ($p > .1$)	.82
Mean *R*	.99		.66		.57		.74

Note. The *R* values show that individual and mean coordinates vary systematically; the *t* and *p* values suggest that individual data fall within the same range as the mean.

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phonological store is accessed during auditory processing and when activating phonological information during reading (Coltheart, Davelaar, Jonasson, & Besner, 1977; Rubenstein, Lewis, & Rubenstein, 1971; Van Orden, 1987; but see Caramazza, 1997). Therefore, to differentiate neural pathways devoted to orthographic and phonological processing, orthographic processing was defined as voxels activated during visual, but not auditory, processing. Phonological processing was defined as voxels activated during auditory, but not visual, processing. Only activation consistent across both words and nonwords was considered in the phonological and orthographic analyses, to eliminate activation due to processing word meaning. The approach used to isolate lexical, phonological, and orthographic processing is different from subtraction in that unique responses are identified, and assumptions of linearity do not have to be made (Hirsch et al., 2001).

Measures of spread and central tendency

Volumes of activation measured the number of active voxels and indicated the extent of cortical activation. Volumes of activation in cubic millimeters within the IFG were computed by determining the number of voxels activated for lexical, phonological, and orthographic processing and were taken as a measure of spread. To compare the localizations of activation during L1 and L2 processing, centers of activation (central tendency) for areas that were active in each language were computed. To compute the centers of activation for voxels activated in each language, the *XYZ* coordinates of each activated voxel were identified. For each individual plane, the geometric center was calculated by adding the coordinates and dividing the sum by the total number of voxels. The distance between the two centers of activation in a three-dimensional space was computed as $D = \sqrt{[(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2]}$ where D is the center-to-center distance, X_1, Y_1, Z_1 are the *XYZ* coordinates in a three-dimensional space of the center of mass in L1, and X_2, Y_2, and Z_2 are *XYZ* coordinates in a three-dimensional space of the center of mass in L2. Only activations with two or more voxels were considered for these analyses.

Within the left IFG, distances were computed between centers of activation associated with L1 and L2 lexical, phonological, and orthographic processing. For phonological processing, between-language distances within the left IFG were compared to between-language distances within the left STG since these areas showed activation for all participants during phonological processing. For lexical and orthographic processing, the STG was not consistently active in all participants; therefore, between-language distances in the IFG were compared to within-language distances in the IFG. Within-language center-to-center distances were calculated by comparing centers of activation in Run 1 versus Run 2. Only 5 participants were included in the latter analyses because English within-language data for 1 participant were lost. Within-language center-to-center distances across runs confirmed that activations within a participant were reliable and that between-language distances were valid measures of cross-linguistic patterns, as opposed to artifacts of repeated testing and within-subject variation.

RESULTS

Lexical processing

The areas that were active during lexical processing of L1 and L2 are summarized in Table 3. The IFG (BA 44, 45, and 46) was active bilaterally for both the first and the second languages, suggesting that the homologue of Broca's area in the right hemisphere was also involved in lexical processing. Activation in the STG (BA 22) was less consistent across participants. Areas activated during lexical processing are listed in Table 3 and include the middle and medial frontal gyri, the middle temporal gyrus, the inferior parietal lobe, and others.

Volumes of cortical activation associated with lexical processing of each language in the IFG are reported in Table 4. Across both languages, the left IFG was significantly more active than the right IFG (Wilcoxon $T = 66$, $N = 12$, $p = .04$). Within the IFG, L2 activated a larger cortical volume than L1 across both hemispheres (Wilcoxon $T = 77$, $N = 12$, $p = .001$).

Between-language and within-language center-to-center distances in the IFG are shown in Table 5. The mean distance in the IFG between centers of activation associated with lexical processing of L1 and L2 translation equivalents was 7.1 mm ($SD = 4.7$). The mean distance in the IFG between centers of activation associated with lexical processing of different words in the same language was 3.8 mm ($SD = 1.7$). The between-language center-to-center distance was significantly larger than the within-language center-to-center distance (Wilcoxon $T = 49$, $N = 5$, $p = .01$).

Figure 1 shows a representative image of cortical activation observed during lexical processing in the first and second languages.

TABLE 3
Cortical regions activated for lexical, phonological, and orthographic processing in the left and right hemispheres

		Left hemisphere	*Right hemisphere*
Lexical	L1	GFi 6, GFm 4, GFs 1, GFd 4, GTs 2, GTm 4, GTi 1, LPi 3, Gsm 1, Ga 1, LPs 1, GPrC 3, GPoC 2, GOccipitalis 3	GFi 5, GFm 3, GFs 1, GFd 3, GC 2, GTs 4, GTm 3, Gsm 1, Ga 1, GPrC 2, GOccipitalis 3
	L2	GFi 6, GFm 4, GFd 4, GC 1, GTs 1, GTm 3, GTi 3, LPi 4, Gsm 1, Ga 3, LPs 2, GPrC 4, GPoC 1, GOccipitalis 2, GF 1	GFi 6, GFm 4, GFs 1, GFd 5, GC 3, GTs 4, GTm 2, GTi 1, LPi 1, Gsm 1, Ga 2, LPs 1, GPrC 4, GOccipitalis 2, GF 1
Phonological	L1	GFi 6, GFm 4, GFs 1, GFd 4, GC 1, GTs 6, GTT 2, GTm 6, Gsm 1, Ga 1, GPrC 4, GPoC 3	GFi 6, GFm 2, GFs 1, GFd 2, GC 1, GTs 6, GTT 4, GTm 6, GTi 1, LPi 3, Ga 1, GPrC 5
	L2	GFi 6, GFm 6, GFs 4, GFd 4, GC 3, GTs 6, GTT 3, GTm 5, LPi 5, Gsm 2, LPs 1, GPrC 6, GPoC 3, GOccipitalis 4, GF 1	GFi 5, GFm 5, GFs 2, GFd 5, GC 3, GTs 6, GTT 2, GTm 5, LPi 4, Gsm 2, Ga 3, LPs 1, GPrC 5, GOccipitalis 2, GF 1
Orthographic	L1	GFi 6, GFm 5, GFs 1, GFd 5, GC 1, GTs 1, GTm 6, GTi 6, LPi 6, Gsm 3, Ga 2, LPs 4, GPrC 6, GPoC 2, GOccipitalis 6, GF 4	GFi 6, GFm 4, GFd 4, GTs 3, GTm 4, GTi 3, LPi 3, Gsm 1, Ga 3, LPs 3, PCu 1, GPrC 4, GOccipitalis 6, GF 4
	L2	GFi 5, GFm 4, GFs 1, GFd 3, GC 2, GTm 5, GTi 1, LPi 5, Gsm 2, Ga 2, LPs 3, PCu 1, GPrC 5, GPoC 2, GOccipitalis 6, GF 4	GFi 6, GFm 5, GFd 2, GC 3, GTs 1, GTm 4, GTi 3, LPi 3, Gsm 3, Ga 2, LPs 2, PCu 1, GPrC 3, GOccipitalis 6, GF 4

Note. The Latin abbreviations follow the nomenclature used in Talairach and Tournoux (1988). For each area, the number of participants who showed activation of that area is provided next to it.

TABLE 4
Volumes[a] of inferior frontal gyrus activation for lexical, phonological and orthographic processing

	Lexical				*Phonological*				*Orthographic*			
	Left hem.		*Right hem.*		*Left hem.*		*Right hem.*		*Left hem.*		*Right hem.*	
Participant	*Russian*	*English*	*Russian*	*English*	*Russian*	*English*	*Russian*	*English*	*Russian*	*English*	*Russian*	*English*
1	126	189	0	304.5	220.5	357	157.5	2383.5	525	42	903	409.5
2	367.5	546	252	273	21	304.5	504	1879.5	514.5	0	598.5	420
3	598.5	630	105	94.5	52.5	31.5	52.5	126	409	724.5	115.5	220.5
4	31.5	210	21	189	63	976.5	94.5	766.5	441	147	73.5	10.5
5	115.5	189	147	262.5	42	357	63	430.5	31.5	388.5	52.5	42
6	661.5	2457	42	451.5	105	73.5	199.5	0	1575	1407	10.5	42
Mean	316.7	703.5	94.5	262.5	84	350	178.5	931	582.6	451.5	292.2	190.7
SD	267.9	880.7	94.6	119.3	72.44	338.4	169.2	979.9	518.9	539.5	369.5	188.7

[a]In mm^3.

Phonological processing

During phonological processing, the inferior frontal gyrus and the superior temporal gyrus were bilaterally active in all 6 participants. Other areas activated included middle and medial frontal gyri, the middle temporal gyrus, the inferior parietal lobe, and others as listed in Table 3. Volumes of cortical activation associated with phonological processing of each language in the IFG are reported in Table 4. The left and right IFG did not differ in volumes of activation (Wilcoxon $T = 51$, $N = 11$, $p = .15$). Within the IFG, L2 activated a larger cortical volume than L1 in both hemispheres (Wilcoxon $T = 66$, $N = 12$, $p = .03$). The mean between-language distance in the IFG was 7.0 mm ($SD = 4.4$), and the mean between-language distance in the STG was 2.9 mm ($SD = 1.3$). The center-to-center distance between languages was significantly larger in the inferior frontal gyrus than in the superior temporal gyrus (Wilcoxon $T = 15$, $N = 12$, $p = .03$). Figure 2 shows a representative image of cortical activation observed during phonological processing in the first and second languages.

Orthographic processing

For activation unique to orthographic processing, the left inferior frontal gyrus was active in 6

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TABLE 5
Cortical distances[a] between and within languages for lexical, phonological, and orthographic processing within the inferior frontal gyrus

	Lexical			*Phonological*			*Orthographic*	
	Between-language IFG	*Within-language IFG*		*Between-language IFG*	*Between-language STG*	*Between-language IFG*	*Within-language IFG*	
Participant		*Russian*	*English*				*Russian*	*English*
1	2.0 (L)	4.3 (L)	4.7(L) 2.1(R)	9.8(L) 1.9(R)	3.1(L)	9.2(L) 7.8(R)	4.1(L) 3.6(R)	3.8(R)
2	3.96(L) 2.8(R)	N/A	N/A	5.74(L)	2.23(L)	4.2(R)	N/A	N/A
3	5.5(L) 6.3(R)	6.2(L) 2.8(R)	4.8(L) 1.9(R)	12.4(L) 3.4(R)	2.4(L)	2.8(L) 2.1(R)	6.3(L) 3.3(R)	7.2(R)
4	5.7(L) 14(R)	1.77(L)		4.8(L) 1.7(R)	1.9(L)	1.1(L)	2.7(L)	
5	15.2(L)	6.5(L) 3.8(R)	3.7(L) 2.3(R)	13.4(L)	5.4(L)	2.1(L)	1.5(L) 2(R)	2.2(L)
6	8.7(L)	3.6(L) 1.5(R)	6(L) 4.4(R)	9.5(L)	2.1(L)	2.6(L)	6(L)	2.4(L)
Mean	7.1	3.7	3.7	7.0	2.9	4.0	3.7	3.9
SD	4.7	1.7	1.5	4.4	1.3	2.9	1.7	2.3

Note. Distances within the left IFG are noted as (L), and distances within the right IFG are noted with (R).
[a]In mm.

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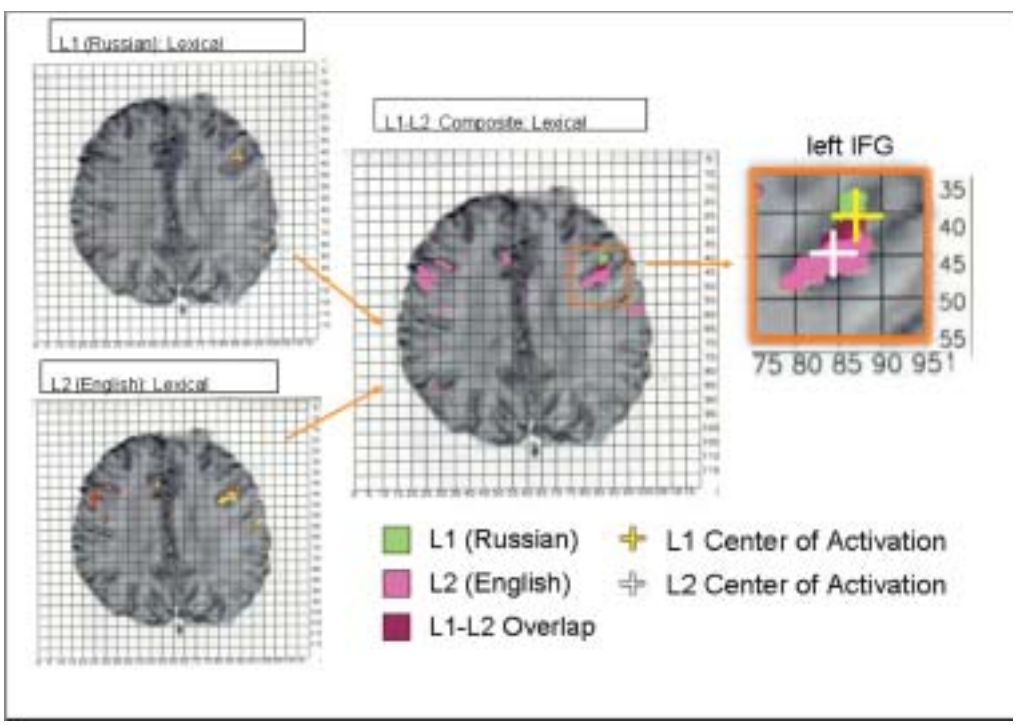

Figure 1. A representative image of cortical activation observed during bilingual lexical processing shows shared and unique areas of activation for the two languages. The first column shows separate activations associated with lexical processing in the first language (Russian) and the second language (English). The second column shows a superimposed image of all activations observed during lexical processing, with activation unique to L1 marked in green, activation unique to L2 marked in pink, and activation overlapping across languages marked in maroon. A close-up of left IFG with cross-hairs indicating different centers of activation associated with each of the two languages is also included, $p < .05$. (Centers of activation were computed in a three-dimensional space and may therefore not appear centered on the z-plane shown, Talairach $z = +28$.)

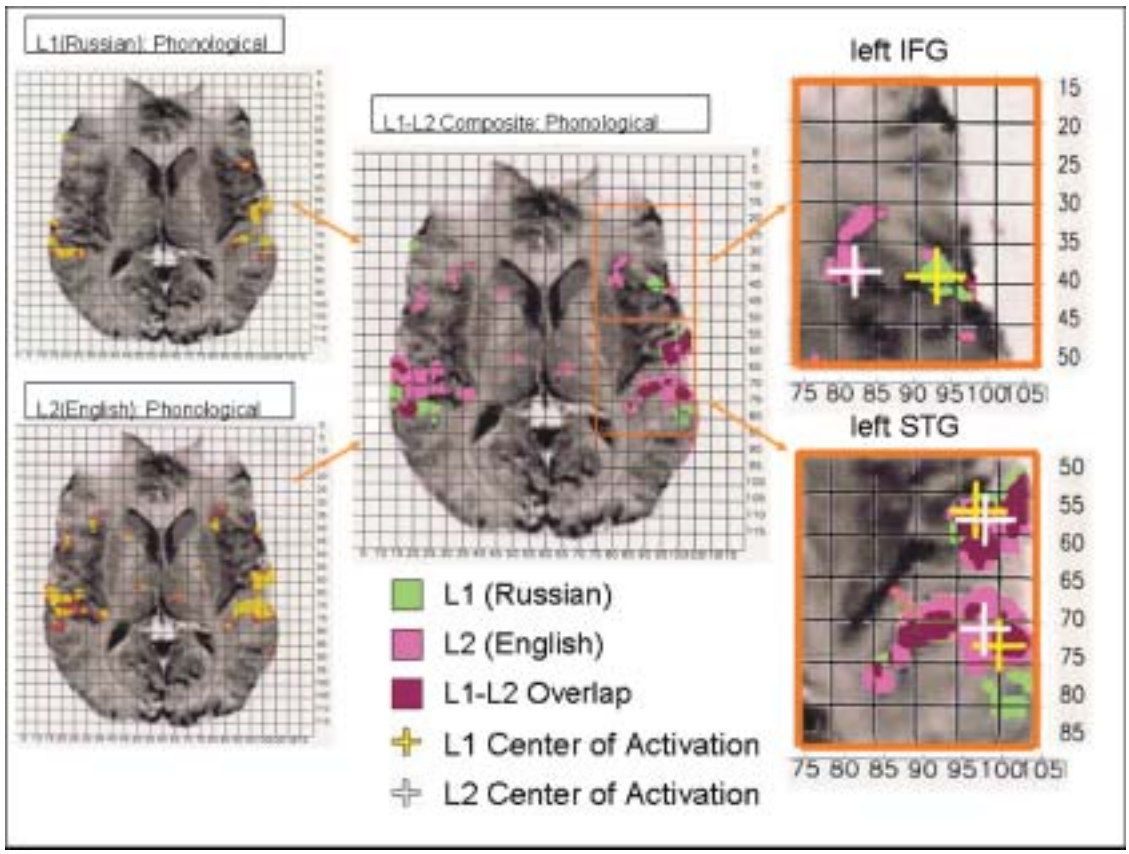

Figure 2. A representative image of cortical activation observed during bilingual phonological processing shows shared and unique areas of activation for the two languages. The first column shows separate activations associated with phonological processing in the first language (Russian) and the second language (English). The second column shows a superimposed image of all activations observed during phonological processing, with activation unique to L1 marked in green, activation unique to L2 marked in pink, and activation overlapping across languages marked in maroon. Close-ups of left IFG and left STG with cross-hairs indicating the centers of activation (calculated in three-dimensional space) associated with each of the two languages are also included. The difference between centers of activation was greater in the IFG than in the STG, $p < .05$. Note that two different clusters of activation were present in the left STG. The centers of activation in the bottom cluster, corresponding to BA 22, fell onto the axial slice shown (Talairach $z = +12$) and were included in the figure. Centers of activation in the top cluster, corresponding to BA 42, fell onto a different axial plane ($z = +8$), but were transposed onto the plane shown in the figure for purposes of graphical representation (the distance between centers was maintained).

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participants for L1 and in 5 participants for L2, and the right IFG was active in all participants for both L1 and L2. Another structure consistently active across all 6 participants during orthographic processing was the occipital cortex. The STG was not consistently active in all participants (see Table 3). Other cortical areas active during orthographic processing included the fusiform gyrus, the inferior parietal lobe, the middle temporal gyrus, and the middle and medial frontal gyri.

Across both languages, the left and right IFG did not differ in volumes of activation (Wilcoxon $T = 47$, $N = 12$, $p = .62$). Activation in L2 and L1 also did not differ significantly (Wilcoxon $T = 55$, $N = 12$, $p = .23$). Individual and group data are presented in Table 4. The mean between-language distance in the IFG was 4.0 mm ($SD = 2.9$), and the mean within-language distance in the IFG was 3.7 mm ($SD = 1.8$); the difference between the two was not significant. Figure 3 shows a representative image of cortical activation observed during orthographic processing in the first and second languages.

DISCUSSION

In this study, we examined cortical activation associated with lexical, phonological, and orthographic processing of L1 and L2 in a homogeneous group of highly proficient late Russian–English bilinguals. Results revealed similarities as well as differences across lexical, phonological, and orthographic processing. A number of patterns emerged and are discussed at different levels of cortical detail:

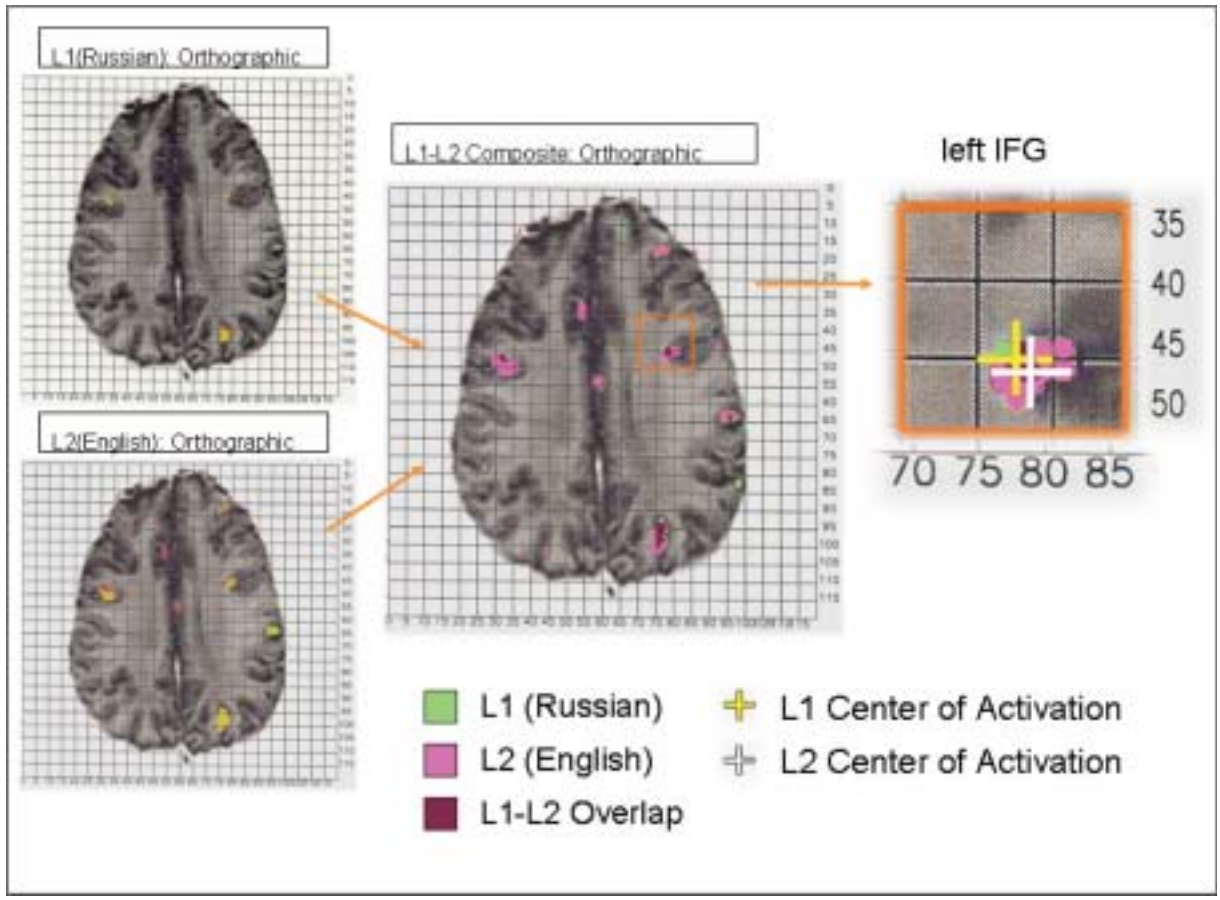

Figure 3. A representative image of cortical activation observed during bilingual orthographic processing shows areas of activation associated with the two languages (Talairach $z = +28$). The first column shows the separate activations associated with orthographic processing in the first language (Russian) and the second language (English). The second column shows a superimposed image of all activations observed during orthographic processing, with activation unique to L1 marked in green, activation unique to L2 marked in pink, and activation overlapping across languages marked in maroon. (More extensive activation of the occipital cortex was present at lower axial slices.) A close-up of IFG with cross-hairs indicating centers of activation associated with each of the two languages (calculated in three-dimensional space) is also included ($p > .1$).

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hemispheric lateralization of first and second languages, volumes of activation, structures activated, and centroid comparisons.

Hemispheric lateralization

The right hemisphere was involved in both L1 and L2 processing in all participants. Frequently activated right hemisphere areas for both L1 and L2 included the inferior frontal gyrus, the superior temporal gyrus, and the inferior parietal lobe. These areas were also active in the left hemisphere. In this group of late bilinguals, the prediction of overall greater right hemisphere lateralization of L2 was not supported.

IFG was bilaterally activated for lexical, phonological, and orthographic processing. The pattern of increased activation during L2 processing was observed in both the right and the left IFG for lexical and phonological processing, but not for orthographic processing. The involvement of the right homologue of Broca's area (right IFG) in language processing is frequently reported in neuroimaging studies with normal monolingual and bilingual participants, as well as in studies of language recovery in aphasic individuals (e.g., Ansaldo, Arguin, & Lecours, 2002; for reviews, see Abutalebi et al., 2001; Green & Price, 2001).

Greater cortical activation was observed in the left IFG than in the right IFG for lexical processing. This finding is consistent with the view that the left hemisphere is dominant for language processing, even in bilinguals (Roberts, Sostheim, & Kubota, 2001). However, phonological and orthographic processing were associated with similar activation volumes in the IFG across both hemispheres. Individual participant data revealed high

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variability in the extent of right hemisphere activation within the IFG during phonological and orthographic processing, ranging from no activation to over 2,000 mm^3 of activation in the right IFG. (For instance, Participant 2 showed bilateral activation in processing L1 orthography, but only right IFG activation when processing L2 orthography, supporting the argument that patterns of cortical activation involved in L1 and L2 processing are subject to individual differences. It is difficult to pinpoint exactly the source of this variability as it may be due to multiple factors, such as the exact age of L2 acquisition and relative language proficiency.) The observed individual differences are consistent with earlier findings of high interindividual variability in cortical organization and function (e.g., Dehaene et al., 1997). This variability was greater during processing of the second language than during processing of the first language (e.g., Dehaene et al., 1997; Mehler, Pallier, & Christophe, 1998) and has been taken as support for the hypothesis that first-language acquisition relies on a dedicated left hemispheric cerebral network, while second-language acquisition is not necessarily associated with consistent cortical structures.

Spread of activation

Results revealed greater activation within the IFG for L2 than for L1 for lexical and phonological processing. This is consistent with earlier findings of greater L2 activation in proficient bilinguals during cued word generation tasks (Abutalebi et al., 2001) and during sentence comprehension tasks (Rüschemeyer, et al., 2005). These results are also consistent with reports of greater activation for a less proficient second (and third) language than for the more proficient first language (Hasegawa et al., 2002; Vingerhoets, et al., 2003; Yetkin et al., 1996). One possible explanation for the increased activation observed during second-language processing is that acquisition of new languages relies not only on established neural networks of earlier learned languages, but also on additional novel connections for later learned languages.

Another possible explanation is that processing a later learned language may be more demanding, resulting in recruitment of additional neural resources. For example, greater frontal activation has been associated with increased processing demands in both linguistic (e.g., Thompson-Schill et al., 1998) and nonlinguistic tasks (e.g., Huettel & McCarthy, 2004). Some studies have linked greater IFG activity with lower language ability in both monolinguals (Blumenfeld, Booth, & Burman, in press) and bilinguals (Tatsuno & Sakai, 2005). Although bilinguals in the present study were highly proficient in both languages (with high English proficiency evident from scores on standardized academic tests and high Russian proficiency indicated by late arrival to the US and schooling in the native language), absence of direct comparisons between L1 and L2 language abilities leaves open the possibility that some differences in proficiency were present and may have contributed to the observed pattern of results.

The increased activation associated with the second language was not observed for orthographic processing, possibly because IFG is not a primary activation site for orthographic processing. Alternatively, it is possible that bilinguals use the same orthographic processing strategies for both L1 and L2, as suggested by Nakada, Fujii, and Kwee (2001).

Cortical regions and central tendency

Similar cortical regions (IFG, STG, etc., see Table 3) were activated for L1 and L2 in the right and left hemispheres, a result consistent with Chee et al. (1999b), Illes et al. (1999), Kim et al. (1997), and Perani et al. (1998), suggesting that learning a second language after puberty recruits cortical regions that are already involved in L1 processing. However, within these generally similar structures, differences in centers of activation for first- versus second-language processing were observed. These results are consistent with findings by Kim et al. (1997) that both the IFG and the STG are active during first- and second-language processing in late bilinguals, but that within the STG the centers of activation for the two languages are generally overlapping, while within the IFG the centers of activation for the two languages are distinct.

The present study revealed that, during phonological processing, the between-language distance in the IFG was greater than the between-language distance in the STG. This finding extends the results of Kim et al. (1997) from language production to language comprehension and suggests that L1 and L2 engage at least partially distinct cortical networks within the IFG in late bilinguals. For lexical processing, between-language distance in the IFG was greater than within-language distance in the IFG. For orthographic processing, between-language distance in the IFG did not differ from within-language distance in the IFG, perhaps because the IFG is not a primary cortical region for processing orthographic information. This

finding is consistent with that of Nakada et al. (2001), who found no difference in activation patterns for L1 vs. L2 orthographic processing in Japanese–English bilinguals. Between-language differences in orthographic processing may be more evident in studies with an explicit objective to focus primarily on areas involved in orthographic processing, such as the occipital cortex, as well as fusiform and inferior temporal gyri.

Gender effects

Although the sample size was too small to establish gender differences, exploratory comparisons on the effects of gender were conducted. In the 3 males and 3 females tested, a tendency was observed for males to show more activation in the left hemisphere than in the right hemisphere. Females activated both hemispheres approximately equally during L1 processing and tended to activate the right hemisphere more than the left hemisphere during L2 processing. On average, males had 478 mm^3 active in the left IFG and 208 mm^3 active in the right IFG for Russian, and 686 mm^3 in the left IFG and 389 mm^3 in the right IFG for English. Females had an average of 177 mm^3 active in the left IFG and 168 mm^3 active in the right IFG for Russian, and 317 mm^3 in the left IFG and 533 mm^3 in the right IFG for English. These results suggest that males may rely on the left hemisphere more than females for language processing, whereas females may show less left-hemisphere language lateralization, a finding consistent with earlier results (Shaywitz et al., 1995a). Moreover, because gender differences are likely to affect lateralization, care should be taken when selecting bilingual participants and when interpreting results. Tables 4 and 5 can be visually inspected for additional observations regarding data from female and male participants (Participants 1, 4, 5 vs. 2, 3, 6, respectively).

GENERAL DISCUSSION

In the present study, neural correlates of L1 and L2 varied across levels of processing in a manner parallel to that reported in the monolingual literature. Specifically, the inferior frontal gyrus has been implicated in both lexical (Burton, LoCasto, Krebs-Noble, Gullapalli, 2005; Ischebeck et al., 2004; Xiao et al., 2005) and phonological processing (e.g., Shaywitz et al., 1995). The presence of IFG activation in bilinguals, as well as the presence of between-language differences at this site, confirm that IFG plays a crucial role in lexical and phonological processing. Further, activation was similar across both L1 and L2 in areas associated with processing of modality-specific orthographic and phonological information—that is, STG for phonological processing and occipital cortex for orthographic processing. This suggests that L1/L2 processing relies on similar modality-specific substrates and that these sites do not appear to be sensitive to between-language differences in the same way as is the IFG.

It is important to acknowledge that the sample size in the present study, as in other neuroimaging studies with bilinguals (Hernandez et al., 2001; Hernandez et al., 2000; Leung et al., 2002; Wang et al., 2003), is relatively small and may limit generalizability of findings. Strictly speaking, the statistical conclusions drawn in the current research apply properly over the domain of subjects studied and await replication with other bilingual groups to extrapolate to the bilingual population from which they were drawn. Although that is generally the case, and one should proceed with caution when generalizing results, the majority of findings in the present study were consistent across participants, suggesting that the observed effects may extend to bilinguals who are similar to those tested.

In general, a number of factors relevant to bilingualism specifically may influence the pattern of activation during first- and second-language processing. In addition to aforementioned individual differences and gender effects, age of L2 acquisition and proficiency in the two languages are particularly likely to influence bilingual cortical organization. In the present study, spread-of-activation differences are likely due to variability in proficiency levels (e.g., Hasegawa et al., 2002; Vingerhoets et al., 2003), while center-of-activation differences are likely due to variability in age of L2 acquisition (e.g., Kim et al., 1997). However, it is difficult to pinpoint with certainty the individual contributions of the two. Because age of acquisition and level of proficiency often go hand in hand, teasing apart their separate influences on bilingual language functioning is an important avenue for future research. Further, patterns of activation may be mediated by how similar two languages are, with languages that are very different from each other (e.g., tonal vs. nontonal languages, alphabetic vs. logographic languages, etc.) more likely to diverge in neural underpinnings. Moreover, differences between neural correlates of L1 and L2 can also be studied by manipulating between-language overlap within words. For example, future neuroimaging research may examine cortical activation associated with processing of cognates (words that share both form and

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meaning across languages), homophones (words that sound the same but carry different meanings), homographs (words that look the same in written form but carry different meanings across languages), translation equivalents that do not share form, and words that share neither form nor meaning across languages.

In general, differences in cortical activation patterns for L1 and L2 may stem from multiple sources. For instance, one possible explanation may rely on representational differences, with the two languages represented in somewhat distinct cortical regions. The more extensive activation in the frontal lobe during L2 processing than during L1 processing may therefore be representational in nature. Alternatively, the observed cortical differences may be due to variability in processing demands, with different allocations of attention and/or effort devoted to processing L1 versus L2. L2 may recruit the frontal lobe to a greater extent not because it is represented differently, but because it involves greater processing demands and more cognitive resources, for example as a result of varying levels of proficiency across the two languages. Other factors, such as attention to ambient noise in the scanner room, may have influenced the results as well, to an unknown degree. As fMRI and other neuroimaging techniques evolve, such limitations will become increasingly minimized, making it possible to examine bilingual language processing in the context of different experimental tasks, stimuli, presentation modalities, and subject populations. Factors such as manner of acquisition (e.g., classroom vs. everyday life), modality (auditory vs. visual vs. tactile), task selection (e.g., rhyming vs. synonym generation vs. word-stem completion, etc.), type of processing (e.g., orthography, phonology, lexicon), and participant language history are all likely to impact neural correlates of bilingual language processing. To allow generalizability of the present findings to other bilingual populations, future research will need to examine the individual and combined influences of these variables on bilingual cortical organization.

Finally, a more accurate understanding of cortical bases for bilingual language organization and processing carries important clinical implications, for instance in preoperative planning affecting frontal and temporal lobes in multilingual individuals. In the long run, convergence of behavioral and neuroimaging methodologies may also enhance clinical abilities to diagnose and treat language disorders in multilingual children and adults. For instance, neuroimaging research may improve the diagnostics of a language disorder, and, in turn, behavioral diagnosis of a language disorder may provide knowledge about its cortical underpinnings. As we refine our knowledge of which linguistic subsystems overlap and which do not, it may become possible to utilize the overlap in treatment, by structuring treatment so as to capitalize on the overlap and bootstrap to nonoverlapping aspects for maximum treatment efficacy. In this way, neuropsychological studies of first- and second-language processing have the potential to impact theoretical and clinical discussions of bilingualism and the general human linguistic capacity.

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