Available online at www.sciencedirect.com

SCIENCE DIRECT®

ACADEMIC PRESS

Brain and Language 86 (2003) 70–82

Brain and Language

www.elsevier.com/locate/b&l

Shared and separate systems in bilingual language processing: Converging evidence from eyetracking and brain imaging☆

Viorica Marian,[a,*] Michael Spivey,[b] and Joy Hirsch[c]

[a] Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208-3570, USA
[b] Department of Psychology, Cornell University, Ithaca, NY 14853, USA
[c] Center for Neurobiology and Behavior, Columbia University, New York, NY 10032, USA

Accepted 23 July 2002

Abstract

The neurological and cognitive aspects of bilingual language processing were examined in late Russian–English bilinguals using headband-mounted eyetracking and functional neuroimaging. A series of three eyetracking studies suggested that, at early stages of word recognition, bilinguals can activate both languages in parallel, even when direct linguistic input is in one language only. A functional neuroimaging study suggested that, although the same general structures are active for both languages, differences within these general structures are present across languages and across levels of processing. For example, different centers of activation were associated with first versus second language processing within the left Inferior Frontal Gyrus, but not within the Superior Temporal Gyrus. We suggest that parallel activation (as found with eyetracking) and shared cortical structures (as found with fMRI) may be characteristic of early stages of language processing (such as phonetic processing), but the two languages may be using separate structures at later stages of processing (such as lexical processing).

Keywords: Bilingualism; Language; Eyetracking; Brain; fMRI; Parallel Processing; Semantics; Phonology

1. Introduction

The objective of the present work was to explore bilingual language processing by integrating behavioral and neuroimaging data. We describe three eyetracking ex-

☆ The authors thank Ulric Neisser for helpful comments and feedback on this work, Eugene Shildkrot for assistance with the project, Olga Kats, Marina Basina, Nora Chan, Krista Bendig, and Alex Raichev for assistance with the eyetracking experiments, and Karl Kim, Yasmeen Faroqi-Shah, Li Sheng, and the members of the fMRI laboratory at the MSKCC for assistance with the fMRI study. This work was supported in part by a Developmental Training Grant (NIH 5T32MH01938909) to the first author.
* Corresponding author. Fax: 1-847-467-2776.
E-mail address: v-marian@northwestern.edu (V. Marian).

0093-934X/03/$ - see front matter
doi:10.1016/S0093-934X(02)00535-7

periments and a functional neuroimaging study that examined how bilingual speakers process linguistic input. Both methodologies were used to examine single-word processing and the results are interpreted within the context of a distinction between the cognitive architecture for phonetic processing, where the two languages appear to operate simultaneously, and the cognitive architecture for lexical processing, where selective activation may take place.

A number of previous studies have suggested distinct non-overlapping cortical representations of the two languages in bilinguals. For example, selective impairment and/or differential recovery of one or more languages have been reported in multilingual aphasic patients (e.g., Nilipour & Ashayeri, 1989; Paradis & Goldblum, 1989). Selective disruption of first and second language naming has been reported in cortical stimulation studies (e.g., Ojemann & Whitaker, 1978) and different Event Related Potential (ERP) patterns have been observed in first language processing of bilinguals and monolinguals (e.g., Donald, Meuter, & Ardal, 1986). However, a number of other studies have found evidence for overlapping cortical representations in bilinguals. Event Related Potential patterns of Farsi–English bilinguals involved the same cortical regions for both languages (Sarfarazi & Sedgwick, 1996). Overlapping regions of activation in the left Inferior Frontal Gyrus were found for both languages in French–English bilinguals using Positron Emission Tomography during semantic and phonological processing (Klein, Milner, Zatorre, Meyer, & Evans, 1995). Empirical findings of locations of activation for the two languages using functional Magnetic Resonance Imaging have also been contradictory. While Kim, Relkin, Lee, and Hirsch (1997) found that late bilinguals activated separate regions for each language within the Inferior Frontal Gyrus, Chee, Tan, and Thiel (1999) found that late bilinguals activated the same regions for both languages in frontal, temporal, and parietal lobes. Illes et al. (1999) found identical frontal lobe region activations for both languages during semantic processing in Spanish–English bilinguals.

Similar to research on cortical organization in bilinguals, behavioral studies of bilingual language processing have also yielded mixed results. Some have suggested separate activation of L1 and L2 (e.g., Gerard & Scarborough, 1989; MacNamara & Kushnir, 1971). Gerard and Scarborough (1989), for example, found that significantly less time is required to make a lexical decision task following a same-language repetition than a different-language repetition, suggesting that extra processing time may be necessary to switch off one lexicon and switch on the other. More recent studies, however, suggest simultaneous activation of the two languages (e.g., Bijeljac-Babic, Biardeau, & Grainger, 1997; Dijkstra, 2001; van Heuven, Dijkstra, & Grainger, 1998). Bijeljac-Babic et al. (1997), for example, used a masked priming paradigm to study orthographic priming in bilinguals and found that briefly presented printed strings of letters can simultaneously activate lexical representation in both languages even when participants are performing a seemingly monolingual task.

These inconsistencies in the literature have been explained in the past by differences in methodologies and/or subject populations (e.g., Grosjean, 1998). We suggest that another parsimonious way to reconcile the different findings within the cognitive literature and within the neurological literature on bilingualism is by distinguishing between different bilingual processing styles for phonetic information and for lexical information. The results we report are consistent with the following hypothesis: The real-time mapping of acoustic–phonetic input to lexical items in a bilingual takes place in parallel for the two languages even when in a purely monolingual environment, however, complete activation of these lexical items is somewhat limited to the language being used.

The results of the eyetracking studies reported here suggest that, at early stages of word recognition, bilinguals activate both languages in parallel, even when direct linguistic input is in one language only. For example, when instructed in English to "pick up the marker," Russian–English bilinguals often looked briefly at a stamp, because its Russian name, 'marka', has phonological overlap with the English spoken word, 'marker'. In instances of simultaneous competition from both languages, both within-language competition and between-language competition were observed. The functional neuroimaging study indicated that the same general structures were active for both languages (the Inferior Frontal Gyrus, the Superior Temporal Gyrus, the Middle Temporal Gyrus, the Precentral Gyrus, the Angular Gyrus, the Supramarginal Gyrus, and the Extrastriate cortex), but not all structures were active at each level of processing. For example, the Superior Temporal Gyrus was found consistently active during phonological processing, but not during lexical processing. In addition, different centers of activation were associated with first versus second language processing within the left Inferior Frontal Gyrus, but not within the Superior Temporal Gyrus.

2. Eyetracking experiments

Three experiments tested spoken language processing at the sub-lexical levels using bilinguals' eye movements. Experiment 1 examined whether both languages are active in parallel or whether bilinguals activate the two languages separately. Experiments 2 and 3 aimed to replicate the results of Experiment 1 and also asked the following two questions: (1) Do bilinguals, similar to monolinguals, activate multiple lexical items within the same language simultaneously? and (2) What happens under circumstances in which lexical items compete for activation both between- and within-languages at the same time?

In previous research with monolingual English speakers, it was demonstrated that listeners frequently look briefly at a "cohort" object with a phonologically similar name (e.g., a candle) when instructed to pick up a target object, e.g., "Pick up the candy" (Allopenna, Magnuson, & Tanenhaus, 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). To test whether the two language systems in bilinguals are simultaneously active during spoken language comprehension, we gave participants instructions in one language (e.g., "Podnimi marku" [Pick up the stamp]), and we recorded when their eyes fixated the stamp, a marker ("flomaster," in Russian), and control distractor objects (Spivey & Marian, 1999). If the phonological uptake of one language is "switched off" while the other is being used, then one would not expect to see eye movements to the "between-language cohort" object, e.g., the marker, when instructed to "Podnimi marku".

The second experiment was designed to replicate the first experiment and extend the paradigm to test for eye movements to within-language competitor objects *within* the first and second languages (e.g., karta [map] vs. kartoshka [potato], and marker vs. marbles,), as well as to pit within-language cohort objects against between-language cohort objects (e.g., karta [map] and a car, when instructed to "Podnimi kartoshku" [Pick up the potato]) (Marian & Spivey, 1999). While the first and second experiments tested participants in both languages, with one block of trials presented in the first language (Russian) and the other block of trials presented in the second language (English), the third experiment tested participants in one language only. With half of the participants tested only in their first language and half tested only in their second language, we could be certain that each subject was in as monolingual a language mode as experimental conditions could possibly achieve

(Marian & Spivey, submitted). For a review of the eyetracking methodology and its use to index language activation see Tanenhaus, Magnuson, Dahan, and Chambers (2000).

2.1. Methods

2.1.1. Participants

All three experiments tested late Russian–English bilinguals fluent in both languages. Fifty-five bilinguals were tested across the three experiments, all grew up in former Soviet Union, immigrated to the United States in their early teens, and were students at a top-tier American University at the time of testing. None of the bilinguals participated in more than one study and all were paid for their participation.

2.1.2. Apparatus

Eye movements were monitored by an eyetracker mounted on top of a lightweight helmet. The camera provided an infrared image of the eye sampled at 60 Hz. The center of the pupil and the corneal reflection were tracked to determine the orbit of the eye relative to the head. A scene camera, mounted on the side of the helmet, provided an image of the subject's field of view. Gaze position was indicated by crosshairs that were superimposed over the scene camera image and recorded onto a Hi8VCR with frame-by-frame audio and video playback. Speech files containing the instructions were recorded and played on a Macintosh computer. For the first two experiments, instructions were pre-recorded by a fluent Russian–English bilingual speaker who acquired both languages in early childhood and had no noticeable accent in either language. For the third experiment, instructions were pre-recorded by monolingual speakers.

2.1.3. Procedure

All participants were tested with 40 trials. In the first two experiments, a block of 20 trials was in English and another block of 20 trials was in Russian. In the third experiment, half of the participants were tested in English only and half were tested in Russian only. Each of the 40 trials consisted of a set of four instructions to the subject: (1) to look at the center cross; (2) to pick up a target object that may or may not have its phonetic competitor(s) present; and (3) and (4) were filler instructions to pick up distractor objects that had no phonetic overlap with the target or each other.

The first experiment tested for between-language competition only. Twenty of the 40 trials were test trials, in which a between-language competitor object was present and the other 20 trials were control trials, with a filler object replacing the between-language competitor. In the test trials, one of the four objects presented in the display was the target object, one was the between-language competitor, and two were filler objects. The between-language competitor was an object whose name in the other language carried phonetic overlap with the name of the target object. For example, if "speaker" was the target object, then "spichki," the Russian word for "matches," was the between-language competitor object. The name of the between-language competitor was never spoken in either language during the entire experiment.

The second and third experiments tested for between-language competition, as well as for within-language competition and for simultaneous competition from both languages. Of the 40 trials, 10 were control trials in which no competitor was present, 10 were between-language competition trials in which a between-language competitor was present, 10 were within-language competition trials in which a within-language competitor was present, and 10 were simultaneous competition trials in which both a between- and a within-language competitors were present. Similar to the first experiment, in the between-language competition condition, one of the four objects in the display was the target object, one was the between-language competitor, and two were filler objects.

In the within-language competitor condition, one of the four objects presented in the display was the target object, one was the within-language competitor, and two were filler objects. The within-language competitor was an object whose name carried phonetic similarity to the target object in the same language. For example, if the English target object was a "speaker," then the within-language competitor was a "spear." Similarly, if the Russian target object was "spichki" (matches), then the within-language competitor was "spitsy" (knitting needles). The name of the within-language competitor was also never spoken in either language during the entire language session.

Finally, in the fourth condition, one of the four objects presented in the display was the target object, one was a between-language competitor, one was a within-language competitor, and one was a filler object. This fourth condition allowed testing a situation in which simultaneous between-language and within-language competition takes place. The four conditions were intermixed throughout the experiment; the order of presentation was varied across subjects.

2.1.4. Stimuli

Using the International Phonetic Alphabet, stimuli were selected so that competitors shared at least two onset phonemes with the target. The amount of phonetic overlap between-languages was approximately equal to the amount of phonetic overlap within-languages. In addition, the average word frequencies of the target word, the between-language competitor and its corresponding filler, the within-language competitor and its corresponding filler, and the other fillers in the display were controlled as closely as possible, using three different word frequency sources (Lenngren, 1993; Zasorina, 1977; Zeno, Ivens, Millard, & Duvvuri, 1995). All items were concrete nouns, represented a clear exemplar, and were real objects of comparable size and suitable to be placed on a table and moved around.

2.2. Results

In all three experiments, participants made significantly more eye movements to the between-language competitor than to a non-overlapping control object in the same location. In the first experiment, participants looked at the between-language competitor 31% of the time and to the control filler object 13% of the time, $F1(1,11) = 8.56,\ p < .05$; $F2(1,9) = 12.05,\ p < .01$. In the second experiment, participants looked at the between-language competitor 16% of the time and to the control filler 7% of the time, $F1(1,14) = 7.22,\ p < .05$; $F2(1,16) = 3.48,\ p = .08$. In the third experiment, participants looked at the between-language competitor 13% of the time and to a non-overlapping control filler 6% of the time, $F1(1,27) = 7.171,\ p < .05$; $F2(1,20) = 5.436,\ p < .05$. None of the experiments showed a significant main effect of language or interaction between distractor type and language ($F1 < 1,\ F2 < 1$).

Within-language competition, tested in the second and third experiments, was similarly robust. Participants made more eye movements to a within-language competitor than to a non-overlapping control object in the same location in both experiments. In the second experiment, participants looked at the within-language competitor 21% of the time and to the non-overlapping control filler 9% of the time, $F1(1,14) = 7.6,\ p < .05$; $F2(1,16) = 3.74,\ p = .07$. In the third experiment, participants made eye movements to a phonetically overlapping within-language competitor 16% of the time and to a non-overlapping control filler in the same location on the board 6% of the time, $F1(1,27) = 10.398,\ p < .01$; $F2(1,20) = 11.286,\ p < .01$. No significant interaction with test language was found ($F1 < 1,\ F2 < 1$).

For the simultaneous between- and within-language competition condition, a three-way ANOVA with Type of Competition (Between or Within), Condition (Competitor or Filler), and Language (English or Russian) was performed. The results revealed a main effect of condition, with participants looking at competitor items significantly more often than at non-overlapping control fillers. In the second experiment, participants made eye movements to phonetically overlapping competitors in 16% of the trials and to non-overlapping control fillers in 8% of the trials, $F1(1,14) = 6.92,\ p < .05$; $F2(1,16) = 3.60,\ p = .08$. In the third experiment, participants made eye movements to overlapping competitors on 13% of the trials and to non-competing control fillers in the same location on 6% of the trials, $F1(1,26) = 13.874,\ p < .01$; $F2(1,18) = 13.049,\ p < .01$. No statistically significant effect involving Type of Competition (Within or Between) or Language (English or Russian) was observed in either experiment.

2.3. Discussion

The three eyetracking experiments examined between-language competition during bilingual spoken language processing on a language mode continuum. Although the first two experiments tested participants in both languages (in separate blocks of trials), the third experiment tested each subject in only one of the two languages. Thus, the third experiment shows that even when the participant has every reason to be in a purely monolingual mode (with the irrelevant language seemingly deactivated), the acoustic–phonetic input is nonetheless processed by both languages.

The results from all three experiments indicate that between-language competition is possible from both languages and into both languages. Bilinguals appear to simultaneously accumulate phonetic input into both of their lexicons as a word unfolds in real time, even when the linguistic environment is purely monolingual. However, whether or not between-language competition will manifest itself depends upon a number of variables such as the language mode and the degree of activation of a language (cf. Marian & Spivey, 1999). Although no significant effect of language was observed, simple effect analyses suggest that the magnitude of the between-language competition may differ across the two languages, a hypothesis to be explored in future research. It does not appear to be the case that a bilingual listener can "switch off" one language while using the other (e.g., MacNamara & Kushnir, 1971), but biasing one language and suppressing the other somewhat may be possible.

The results of the within-language competition analyses firmly establish the phenomenon of within-language competition in bilinguals, in both their first and second languages, thus extending the cohort competition observed in the monolingual English eyetracking experiments (Allopenna et al., 1998; Tanenhaus et al., 1995) to the Russian language and to the bilingual domain. The analyses on simultaneous within- and between-language competition did not reveal any consistent reliable interactions between type of competition and language. Although simple effect analyses have indicated numerical differences in the magnitude of competition from the within-language competitor and from the between-language competitor (with within-language competition being somewhat greater), the lack of an interaction prevents us from making any strong claims. Further work will be necessary to explore this possibility.

3. Functional neuroimaging study

The eyetracking experiments provide important insights into bilingual language processing at the behavioral level. How this processing takes place at the cortical level was the focus of a subsequent functional neuroimaging study in which brain structures associated with first and second languages were examined. What are the differences and similarities between first and second language processing? Do the two languages activate common structures? Are the sizes of the activations similar? These are some of the questions that motivated the functional neuroimaging study.

The goals of the study were to compare the cortical areas activated in late bilinguals during processing of first and second languages. Of particular interest were the classical language areas in the Inferior Frontal Gyrus (Broca's area) and in the Superior Temporal Gyrus (Wernicke's area). We aimed to compare the surface area activated by the two languages during lexical and phonological processing, as well as to compare the centers of activation associated with first versus second language processing in the left IFG and the left STG. The surface area analyses in the IFG focused on comparing activations associated with first versus second language processing. Previous research has suggested that L2 semantic processing generated more cortical activation compared to L1 semantic processing (e.g., Klein et al., 1995) and the current study explored this hypothesis in the phonological and lexical domains. Comparing the centers of activation and the distance between centers of activation across languages makes it possible to examine in greater detail areas of activation within specific cortical regions. The hypothesis was that even if both languages activate the same general cortical area, distance analyses may reveal that the two languages activate different areas within that same region.

The lexical analyses were based on the premise that the area involved in lexical processing is the area activated during word processing, excluding the area activated during non-word processing. To identify the areas involved in lexical processing, the areas overlapping across processing both words and non-words were excluded and only areas unique to processing words were considered. The phonology analyses were based on the premise that the area involved in phonetic processing is the area unique to auditory language processing, excluding visual language processing. To identify the areas involved in processing phonology, the areas overlapping across modalities were excluded and only the areas unique to auditory language processing trials were considered.

3.1. Methods

3.1.1. Participants

Six healthy Russian–English bilinguals were tested, 3 males and 3 females. All had acquired their second language (English) after the critical period and were fluent, balanced speakers of both languages. Participants' mean age at the time of the experiment was 21 years, their mean age at the time of arrival in the US was 15 years. Five participants were right-handed, one was ambidextrous, as determined by the Edinburgh Handedness Inventory for assessing the laterality quotient.

3.1.2. The scanner

A 1.5-T General Electric magnetic resonance scanner with a standard head coil and echo-planar imaging were used to obtain T2-weighted images with a gradient echo pulse sequence (echo time, 60 ms; repetition time, 4000 ms; flip angle, 60°). The in-plane resolution was $1.5\,\text{mm} \times 1.5\,\text{mm}$, slice thickness was 4.5 mm. Twenty-one contiguous 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 along sagittal planes at the same axial locations as the T2-weighted images during each imaging session and served as a reference for subsequent anatomical labeling. All acquired images were reconstructed and aligned to correct for movement artifacts and to allow direct spatial comparisons among conditions using a common coordinate system for each subject.

3.1.3. Design and procedure

The study followed a $2 \times 2 \times 2$ design—Language (Russian or English) $\times$ Presentation Mode (Auditory or Visual) $\times$ Lexical Status (Words and Non-words). There were a total of 16 test runs per subject, 2 for each of the 8 conditions. Each run lasted 144 s and consisted of three parts: a baseline period (52 s), a testing period (40 s), and a final baseline period (52 s). Ten images were taken during each of the three parts. Stimuli were presented at a rate of 1 word (or non-word) per two-second interval. Twenty stimuli were presented during each trial. The task involved passive listening and viewing of stimuli. The auditory stimuli were played via tubular headphones. The visual stimuli were backprojected onto a screen and viewed by the subject via a slanted mirror positioned above the head coil.

3.1.4. Stimuli

Forty words were selected or 40 non-words were created for each language. Since each of the eight conditions was run twice, 20 words or non-words were presented during each of the two runs—all the stimuli were presented only once. Stimuli were presented in mixed lists, varying language and modality of presentation. Only concrete nouns that were translation equivalents were used (e.g., brain, horse, umbrella). For words, stimuli were selected so that the approximate word frequency was about the same in both Russian and English across modalities; word frequencies were computed using three different sources (Lenngren, 1993; Zasorina, 1977; Zeno et al., 1995). For non-words, stimuli were constructed in compliance with the rules that govern letter and phoneme combinations in each language (Potiha, 1970; Zasorina, 1979). The length of words and non-words was balanced across languages and across modalities of presentation.

3.1.5. Analyses

Using blood flow data, the areas of activation associated with processing the first and second languages were identified. The size of the activation and the centers of activation for each language were determined and the distance between centers of activation was computed based on the acquisition grid with a resolution of $1.5 \times 1.5 \times 4.5$ mm (X,Y,Z). To compute the center-of-mass for voxels activated in each language, the XYZ coordinates of each activated voxel were identified. For each individual plane, coordinates were added and divided by the total number of voxels. After all centers-of-mass were identified, the distances between L1 centers of activation and corresponding L2 centers of activation were computed.

3.2. Results

Although the same general structures were active for both languages, differences were observed both across languages and across levels of processing in the number of subjects that showed activation of these structures, the total surface of activation, and the centers of activation.

3.2.1. Phonology

During phonological processing, all six participants showed bilateral activation in the Inferior Frontal Gyrus and in the Superior Temporal Gyrus during first language processing as well as during second language processing. When the volumes of activation within the IFG were compared across languages, more activation based on the number of active voxels was found during L2 processing than during L1 processing. In the left hemisphere, the first language activated an average of 84 mm^3 and the second language activated an average of 350 mm^3. In the right hemisphere, the first language activated an average of 178.5 mm^3 and the second language activated an average of 931 mm^3. Across both hemispheres, the second language showed more activation than the first language in 9 out of 12 cases ($t = 66$, $p = .02$, Wilcoxon Signed Ranks Test).

The results showed that the center-to-center distance between languages was significantly higher in the Inferior Frontal Gyrus (8.9 mm) than in the Superior Temporal Gyrus (2.9 mm), $t(5) = 5.213$, $p = .003$. This finding is consistent with the results of Kim et al. (1997), who reported a mean center-to-center differences of 6.43 mm in the Inferior Frontal Gyrus and 1.88 mm in the Superior Temporal Gyrus ($t(5) = 5.43$, $p = .004$). The results of the center-to-center comparisons support the finding that different centers of activation are associated with first and second language processing within the Inferior Frontal Gyrus, but not within the Superior Temporal Gyrus. Moreover, it extends this pattern of results from language production (Kim et al., 1997) to language comprehension.

To summarize, during phonologic processing, L2 activated a larger cortical area than L1 in both hemispheres and different centers of activation were associated with first versus second language processing in the Inferior Frontal Gyrus, but not in the Superior Temporal Gyrus.

3.2.2. Lexical processing

During lexical processing, the left Inferior Frontal Gyrus was active in all six participants during both languages, the right IFG was active in three participants during L1 processing and in five participants during L2 processing. Activation in the Superior Temporal Gyrus was more limited, only two participants showed STG activation in both languages. (The left STG was active in four participants during L1 processing and in three participants during L2 processing, the right STG was active in three participants during L1 processing and in four participants during L2 processing.) The consistent activation of the Inferior Frontal Gyrus suggests that the IFG is actively involved not only in production but also in comprehension, including lexical processing. The limited activation in the Superior Temporal Gyrus made the Inferior Frontal Gyrus the main focus of analyses for lexical processing.

When the total surface area activated was compared across languages, it was found that within the Inferior Frontal Gyrus, the total number of voxels activated during second-language processing was higher than the total number of voxels activated during first-language processing. In the left hemisphere, the first language activated an average of 317 mm^3 and the second language activated an average of 704 mm^3. In the right hemisphere, the first language activated an average of 95 mm^3 and the second language activated an average of 263 mm^3. Across both hemispheres, the second language showed greater activation than the first language in 11 out of 12 cases, $t = 77$, $p = .0005$, Wilcoxon Signed Ranks Test.

When centers of activation in the left IFG were compared across languages, different centers of activation were found active during first versus second language processing. Across all six subjects, the mean center-to-center distance in the left hemisphere was 6.8 mm. The mean center-to-center distance in the right hemisphere was 5.14 mm. These differences between centers of activation in IFG during language comprehension are comparable to the 6.43 mm observed by Kim et al. (1997) in the left IFG in late bilinguals during language production.

Since there was insufficient activation in the Superior Temporal Gyrus for comparing center-to-center differences, a control comparison was conducted, consisting of comparing the between-language distance to the distance between centers of activation when processing different words in the same language. We hypothesized that the distance between centers of activation for different words in the same language will be significantly lower than the distance between centers of activation for words in different languages. Within-language data for one participant were not available, therefore these distance analyses were based on data from five participants only. For lexical processing, the mean cortical distance between centers of activation in the left IFG during processing of Russian versus English was 8.2 mm, $n = 5$. The distance between centers of activation in the left IFG during processing different words in the same language was 3.8 mm, $t = 49$, $n = 5$, $p = .01$, Wilcoxon Signed Ranks test.

To summarize, it was found that during lexical processing, L2 activated a larger IFG area than L1 in both hemispheres and different centers of activation within the left IFG were associated with first versus second language processing.

3.3. Discussion

Analyses revealed some patterns of activation that were consistent across both lexical and phonological processing, as well as other patterns that were unique to one level of processing only. During lexical and phonological processing, the first and the second languages typically activated the same cortical areas, including, for example, the GFi, GTs, GTm, GPrC, Ga, Gsm, and others. These similarities in which cortical regions are activated by L1 and L2 are consistent with previous evidence from ERP, PET, and fMRI studies (e.g., Illes et al., 1999; Klein et al., 1995; Sarfarazi & Sedgwick, 1996) and reinforce the findings that multiple cortical areas are involved in processing language (e.g., Hirsch, Rodriques-Moreno, & Kim, 2001). However, within these similar cortical regions, a number of differences were observed between first and second language processing, as predicted for the centers of activation analyses.

The Inferior Frontal Gyrus was found active during both lexical and phonological processing, suggesting that Broca's area is actively involved in multiple aspects of language processing, including lexical and phonological processing during passive comprehension tasks. In contrast, the Superior Temporal Gyrus (Wernicke's area) was consistently active only in the phonology analyses. Its involvement during auditory processing of language was expected, supporting the crucial role of STG during phonological processing.

As predicted, the second language activated a larger cortical area in the IFG than the first language during both lexical and phonological processing. These findings are consistent with those of Klein et al. (1995), who observed that the second language (English) showed greater activation than the first language (French) in a PET study with proficient, fluent bilinguals. Together, these results suggest that in this population of late bilinguals L2 processing tends to require more cortical resources than L1 processing.

Cross-linguistic comparisons of centers of activation within classical language areas were performed in analyses in which all six participants showed activity in the areas of interest: the Inferior Frontal Gyrus and the Superior Temporal Gyrus during phonological processing, and the Inferior Frontal Gyrus during lexical processing. During phonological processing, the distance between centers of activation within the IFG was significantly larger than the distance between centers of activation within the STG, suggesting that different centers of activation may be associated with first and second language processing in Broca's, but not in Wernicke's area. In the analyses on lexical processing, different centers of activation in the left IFG were observed for first versus second language processing; this distance was larger than the distance between centers of activation between processing different words in the same language.

4. Conclusions

The question of whether bilinguals process their two languages sequentially or in parallel has generated much interest in the bilingual research community. On one side of the argument is language-selective access (Gerard & Scarborough, 1989; Scarborough, Gerard, & Cortese, 1984), on the other is a model of parallel access of the two lexicons (Beauvillain, 1992; Grainger & Beauvillain, 1987; Grainger & Dijkstra, 1992). More and more recent research has substantiated the parallel access hypothesis. The present research provides evidence for the parallel access position from a series of experiments using bilinguals' eye movements to index activation of a language that is not being used. Results suggest that late Russian–English bilinguals activate both the first language and the second language in parallel, even when direct linguistic input is presented in one language only. It seems that sublexical access may be language-independent in the initial few hundred milliseconds of word recognition, but, with time to process context information, irrelevant-language lexical items are inhibited (Grainger & Beauvillain, 1987; see also Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979, for similar effects in monolingual lexical ambiguity resolution). This is consistent with the current position in cognitive science that language processing in general is not a serial search mechanism, but a parallel activation one (Marslen-Wilson, 1987; McClelland & Elman, 1986). There clearly seems to be some interaction and overlap between a bilingual's two languages at the sublexical level. It seems that a better posing of the question is not whether the bilingual lexicon is language-specific or shared, but what is the degree of this interaction and overlap, and what factors influence it?

Analyses aimed at identifying the cortical areas associated with first and second language processing were based on mapping and comparing the acquired brain images to a co-planar stereotaxic atlas of the human brain. The identified structures, although subject to individual differences, revealed certain general patterns in cortical processing of the two languages in late Russian–English bilinguals. The results support the major role that the Inferior Frontal Gyrus plays in language processing and specifically in single-word processing. In addition, it confirms the role of the Superior Temporal Gyrus during phonological processing.

Within these structures, however, differences between the total volumes of activation associated with the two languages (i.e., total activated surface) and differences between centers of activation for the two languages were observed. In the Inferior Frontal Gyrus, for example, the second language was found to activate a larger surface area than the first language during both lexical and phonological processing. Similarly, different centers of activation were observed during first language processing than during second language processing. However, functional mapping at these minute levels is still in its earliest stages. A method such as single-cell recording might be more useful for such investigations, but obvious ethical concerns prevent such work with humans.

To conclude, the functional neuroimaging study revealed some differences as well as some similarities between first and second language processing in bilinguals. Similarities included the general areas and overall pattern of activation (the same Brodmann areas were active in both languages), as well as overlapping activations in the Superior Temporal Gyrus during phonological processing. The differences included amount of activation (greater activity associated with the second language) and different centers of activation within the Inferior Frontal Gyrus.

We would like to suggest that parallel processing of both languages, as observed in the eyetracking experiments, can easily be accounted for by having some cortical structures that are shared by the two languages and other structures that are not. The overlapping activations in the Superior Temporal Gyrus, for example, may be an indication that shared cortical structures may be responsible for parallel activation of both languages at the level of phonological processing and real-time mapping of acoustic–phonetic input onto candidate lexical items. In studying bilingualism it is absolutely necessary, however, to make the distinction between different levels of processing. In this case, a general distinction between phonological and lexical processing, for example, points to simultaneous and shared activation during early stages of processing such as phonetic processing, but not necessarily during later stages of processing such as lexical processing. It is possible that lexical processing of the two languages generates distinct activations, a hypothesis supported in part by the different centers of activation observed in the Inferior Frontal Gyrus during first and second language processing. Future neuroimaging efforts with bilinguals would do well to specify which particular level of processing is under study. This, along with methodological clarifications, may finally make a reconciliation of seemingly contradictory findings in the bilingualism literature possible.

References

Allopenna, P., Magnuson, J., & Tanenhaus, M. (1998). Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language, 38*, 419–439.

Beauvillain, C. (1992). Orthographic and lexical constraints in bilingual word recognition. In R. J. Harris (Ed.), *Cognitive processing in bilinguals* (pp. 221–235). Amsterdam: Elsevier.

Bijeljac-Babic, R., Biardeau, A., & Grainger, J. (1997). Masked orthographic priming in bilingual word recognition. *Memory & Cognition, 25*(4), 447–457.

Chee, M. W. L., Tan, E. W. L., & Thiel, T. (1999). Mandarin and English single word processing studied with functional Magnetic Resonance Imaging. *Journal of Neuroscience, 19*, 3050–3056.

Dijkstra, T. (2001). What we know about bilingual word recognition: A review of studies and models. Plenary address at the *International Symposium on Bilingualism*, Bristol, UK.

Donald, M. W., Meuter, R., & Ardal, S. (1986). Event-related brain potentials in the first and second languages of bilinguals. *Society for Neuroscience Abstracts, 12*(1), 721.

Gerard, L. D., & Scarborough, D. L. (1989). Language-specific lexical access of homographs by bilinguals. *Journal of Experimental Psychology: LMC, 15*, 305–313.

Grainger, J., & Beauvillain, C. (1987). Language blocking and lexical access in bilinguals. *Quarterly Journal of Experimental Psychology, 39*(2), 295–320.

Grainger, J., & Dijkstra, A. (1992). On the representation and use of language information in bilinguals. In R. J. Harris (Ed.), *Cognitive processing in bilinguals* (pp. 207–220). Amsterdam: Elsevier.

Grosjean, F. (1998). Studying bilinguals: Methodological and conceptual issues. *Bilingualism: Language and Cognition, 1*, 131–149.

Hirsch, J., Rodriques-Moreno, D., & Kim, K. H.-S. (2001). Interconected large-scale systems for three fundamental cognitive tasks revealed by functional MRI. *Journal of Cognitive Neuroscience, 13*, 389–405.

Illes, J., Francis, W. S., Desmond, J. E., Gabrieli, J. D. E., Glover, G. H., Poldrack, R., Lee, C. J., & Wagner, A. D. (1999). Convergent cortical representation of semantic processing in bilinguals. *Brain and Language, 70*, 347–363.

Kim, K. H. S., Relkin, N. R., Lee, K. M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature, 388*, 171–174.

Klein, D., Milner, B., Zatorre, R., Meyer, E., & Evans, A. (1995). The neural substrates underlying word generation: A bilingual functional-imaging study. *Proceedings of the National Academy of Science, 92*, 2899–2903.

Lenngren, L. (Ed.). (1993). *Chastotnyi Slovari Sovremennogo Russkogo Yazyka (frequency dictionary of modern Russian Language)*. Uppsala: Acta Universitatis Upsaliensis.

MacNamara, J., & Kushnir, S. (1971). Linguistic independence of bilinguals: The input switch. *Journal of Verbal Learning and Verbal Behavior, 10*, 480–487.

Marslen-Wilson, W. (1987). Functional parallelism in word recognition. *Cognition, 25*, 71–102.

Marian, V., & Spivey, M. (1999). Activation of Russian and English Cohorts during Bilingual Spoken Word Recognition. In M. Hahn & S. C. Stoness (Eds.), *Proceedings of the twenty-first annual conference of the cognitive science society* (pp. 349–354). Mahwah, NJ: Lawrence Erlbaum.

Marian, V., & Spivey, M. (submitted). Competing activation in bilingual language processing: Within- and between-language competition.

McClelland, J., & Elman, J. (1986). The TRACE model of speech perception. *Cognitive Psychology, 18*, 1–86.

Nilipour, R., & Ashayeri, H. (1989). Alternating antagonism between two languages with successive recovery of a third in a trilingual aphasic patient. *Brain and Language, 36*, 23–48.

Ojemann, G. A., & Whitaker, H. A. (1978). The bilingual brain. *Archives of Neurology, 35*, 409–412.

Paradis, M., & Goldblum, M.-C. (1989). Selective crossed aphasia in a trilingual aphasic patient followed by reciprocal antagonism. *Brain and Language, 36*, 62–75.

Potiha, Z. A. (1970). *Sovremennoye Russkoye Slovoobrazovaniye (modern Russian word formation)*. Moscow: Izdatelstvo Prosveshenyie.

Sarfarazi, M., & Sedgwick, E. M. (1996). Event related potentials (ERP) as a function of language processing in bilinguals. *Electroencephalography and Clinical Neurophysiology, 99*(4), 347.

Scarborough, D., Gerard, L., & Cortese, C. (1984). Independence of lexical access in bilingual word recognition. *Journal of Verbal Learning and Verbal Behavior, 23*, 84–99.

Spivey, M., & Marian, V. (1999). Crosstalk between native and second languages: Partial activation of an irrelevant lexicon. *Psychological Science, 10*, 281–284.

Swinney, D. (1979). Lexical access during sentence comprehension: (Re)consideration of context effects. *Journal of Verbal Learning and Verbal Behavior, 18*, 645–659.

Talairach, J., & Tournoux, P. (1988). *Co-Planar stereotaxic atlas of the human brain. 3-Dimensional proportional system: An approach to cerebral imaging*. New York: Thieme Medical Publishers.

Tanenhaus, M., Leiman, J., & Seidenberg, M. (1979). Evidence for multiple stages in the processing of ambiguous words in syntactic contexts. *Journal of Verbal Learning and Verbal Behavior, 18*, 427–440.

Tanenhaus, M., Magnuson, J., Dahan, D., & Chambers, C. (2000). Eye movements and lexical access in spoken language comprehension: Evaluating a linking hypothesis between fixations and linguistic processing. *Journal of Psycholinguistic Research, 29*(6), 557–580.

Tanenhaus, M., Spivey-Knowlton, M., Eberhard, K., & Sedivy, J. (1995). Integration of visual and linguistic information during spoken language comprehension. *Science, 268*, 1632–1634.

van Heuven, W. J. B., Dijkstra, T., & Grainger, J. (1998). Orthographic neighborhood effects in bilingual word recognition. *Journal of Memory and Language, 39*, 458–483.

Zasorina, L. N. (1979). *Obrazovaniye Upotrebitelnyh Slov Russkogo Yazyka (formation of common words in the Russian Language)*. Moscow: Russkii Yazyk.

Zasorina, L. N. (Ed.). (1977). *Chastotnyi Slovari Russkogo Yazyka (frequency dictionary of Russian Language)*. Moscow: Russkii Yazyk.

Zeno, S., Ivens, S., Millard, R., & Duvvuri, R. (1995). *The educator's word frequency guide*. Touchstone Applied Science Associates.