Multilingual Listening and Reading: An fMRI study of Russian/English and Spanish/English bilinguals

Edna Andrews[1,3,4], Todd Harshbarger[2,4], Charlotte Sophia Rammell[1]

1. *Duke University Linguistics Program*
2. *Duke University Brain Imaging and Analysis Center*
3. *Duke University Center for Cognitive Neuroscience*
4. *Duke Institute for Brain Sciences*

Keywords: fMRI, listening comprehension, reading comprehension, bilingualism, second language acquisition

Abstract

It is known that while both the L1 and L2 use the same neural areas, activation may differ due to the more controlled processing of the L2 (Abutalebi & Rosa, 2012). This experiment examined the neural correlates of multilingual listening and reading comprehension using fMRI. Methodology was based on the Andrews et al. (2013) longitudinal study. Participants were native, native-like or advanced speakers (CEFR B2-C2) of English and Spanish (N=9) or of English and Russian (N=6). In the first task, participants listened to English, Spanish, and Russian conversation clips. In the second task, participants read silently a series of short texts in English, Spanish, and Russian. Common activation patterns across both languages spoken by participants was found in both listening and reading conditions, further adding to literature that suggests different languages use shared brain structures. This study is the first to focus on differences in fMRI activation across proficiency levels (C1- and C2-level versus B2-level) in two different languages.

0. Abbreviations of structures used in paper

ACC = anterior cingulate cortex

IFG = inferior frontal gyrus

ITG = inferior temporal gyrus

MFG = middle frontal gyrus

MTG = middle temporal gyrus

SFG = superior frontal gyrus

STG = superior temporal gyrus

STS = superior temporal sulcus

1. Introduction

The relationship between language and the brain has been explored through neuroimaging techniques only relatively recently (Bandettini, 2012; for meta-analyses, see Binder et al., 2009; Cabeza & Kingstone, 2000; Liu & Cao, 2016; Price, 2010, 2012). Prior to the onset of this technique, studies of the brain and language relied heavily on lesion-deficit models (Price, 2012). Now, using functional anatomy techniques, it is known that while both the first language (L1) and second language (L2) use the same neural areas, activation may differ due to the more controlled processing of the L2 and the lower efficiency in the use of L2 linguistic knowledge (Abutalebi & Rosa, 2012). The present paper addresses the shared neural correlates of bilingual listening and reading comprehension among highly proficient Spanish-English speakers.

1.1 L1 Speech and listening comprehension

Several areas have been cited as important for speech and listening comprehension. Although previous accounts have heavily cited left hemisphere activation for language, speech comprehension involves bilateral areas (e.g., Andrews, 2014; Hickok & Poeppel, 2004, 2007, 2015; Huth et al., 2016; Lerner et al., 2011; Schirmer et al., 2012). One of the main neural regions activated with listening is the superior temporal sulcus (STS) (Crinion, et al., 2006; Evans, et al., 2014; Narain et al., 2003; Okada, et al., 2010; Scott et al., 2000). Other regions that are important in speech perception and listening comprehension are the anterior temporal areas (including the temporal pole) (Mazoyer et al., 1993; Narain et al., 2003; Price, 2012), right temporal and frontal regions (Kang et al. 1999; Kuperberg et al. 2000; Meyer at al., 2000; Robertson et al. 2000), left medial temporal gyrus (MTG) (Mazoyer et al., 1993), anterior STS and superior temporal gyrus (STG) (Hickock & Poeppel 2007; Humphries et al. 2001; Papathanassiou et al. 2000; Scott et al. 2000), inferior frontal gyrus (IFG) (Papathanassiou et al., 2000), cerebellar cortex (Ackermann et al., 2007; Papathanassiou et al., 2000), and some subcortical regions (Duffau et al., 2008; Menjot de Champfleur et al., 2013; Maldonado et al., 2013; Poeppel & Hickok, 2004). Our study is among the first to incorporate ecologically valid listening stimuli in neuroimaging.

1.2 L1 Reading comprehension

In comparison with spoken language, fewer studies have addressed written language comprehension. In previous studies, reading is shown to involve bilateral activation, and may also be more left-lateralized than speech (e.g., Fiez & Petersen, 1998; Spitsyna et al., 2006). Many studies of text reading attempt to address the neural correlates of single-word reading, although this behavior is not the same as normative, ecologically valid reading. These studies identify the LIFG, left angular gyrus, right STG, and bilateral MFG as areas of activation (Joubert et al., 2004). Sentence reading has been shown to activate the visual cortex bilaterally, left MTG, right IFG, left/right temporal pole, and left motor cortex (Rapp et al., 2004), and left premotor, left inferior parietal, and left/right lateral occipital (Miura et al., 2005). Short text reading activates the left/right lingual gyrus, left/right STS, and other language and oculomotor areas (Henderson et al., 2015). Narrative reading activates the left/right posterior cerebellum, left putamen, left caudate, left thalamus, left/right temporal pole, left/right IFG, left/right MTG, left STS, and left/right precuneus (Xu et al., 2005).

1.3 Multilingual contexts

There is a significant body of evidence demonstrating that the L1 and L2 use the same neural areas for processing language (e.g., Abutalebi, 2008; Hernandez et al., 2000; Paradis, 1990, 2004; Van de Putte et al., 2018; Yang et al., 2017). However, both degrees of activation as well as regions of activations may differ due to the more controlled processing of the L2 and the lower efficiency in the use of L2 linguistic knowledge depending on the levels of proficiency (Abutalebi & Rosa, 2012; Abutalebi, Tettamanti, et al., 2009). These differences contribute to differential neural activation during language processing of the L2 in regions such as the anterior cingulate cortex (ACC), left inferior frontal gyrus (LIFG), basal ganglia, and prefrontal regions (Abutalebi & Rosa, 2012; Abutalebi, Rosa, et al., 2009; Abutalebi, Tettamanti, et al., 2009; Hernandez et al., 2000; Sebastian et al., 2011). These earlier studies did not substantially control for level of proficiency in the L2. The goal of the current research is to provide empirical evidence of proficiency at quantifiable levels and explore the correlations of these data with the scan outcomes.

Early studies that have examined the neural basis of auditory processing of an L2 include comparison of age of acquisition on cortical activation during story comprehension (Perani et al., 1998, pp. 1842-44). In this study, high-proficiency late-acquisition learners (L1=Italian, L2=English acquired after 10 years of age in school), low-proficiency late-acquisition learners (L1=Italian, L2=English acquired after 10 in school, data from Perani et al., 1996), and high proficiency early-acquisition learners (Spanish and Catalan acquired before four years) completed a story comprehension task. For the late acquisition learners, two regional cerebral blood flow (rCBF) measures were taken during two English stories, two Italian stories, baselines of a backwards Japanese story and attentive silence. For the early acquisition learners, four rCBF measures were taken during an L1 story, an L2 story, and a baseline of a backwards Spanish or Catalan story. Analyses indicated that L1 listening activation included the left temporal pole, STS, MTG, and hippocampus. L2 activation was similar to L1 activation for high proficiency late acquisition learners, with activation in the left temporal pole, middle and posterior temporal gyrus, and bilateral hippocampi. Temporal lobe activation may have been due to the memory demands of the story comprehension task. The authors concluded that overall language proficiency is responsible for the differences in activation between the groups (Perani et al., 1998). However, the measures for language proficiency were based on a word translation task.

Other studies have investigated the neural correlates of reading in bilingual populations. In a study of Spanish-English bilinguals, Hernandez et al. (2015) found that single-word reading activates a range of regions, including the IFG, putamen and thalamus. Participants (L1=Spanish, L2=English) saw a written word and silently read the word during an fMRI task. When reading the L2, there was bilateral inferior frontal, subcortical, cerebellar, and middle/inferior temporal activation. L1 results were similar, with the largest activation in the LIFG (Hernandez et al., 2015).[2] Most of these studies, however, fail to account for speakers who are highly proficient in both languages.

One of the first longitudinal neuroimaging studies of multilingualism was Andrews et al. (2013). Bilingual subjects who were already proficient in at least two languages or who were acquiring Russian as an L2/L3 completed a series of three proficiency tests and three fMRI scans of listening and reading tasks . Statistical modeling (multivariate analysis of covariance, MANCOVA) demonstrates that proficiency measures were found to correlate significantly with scan results in the Russian listening and reading conditions over time. That is, the changes in proficiency in individual subjects correlated with the changes in the activations found in the regions of interest (MTG, STG, MFG, IFG, PoG, PrG bilaterally). The results of this longitudinal fMRI study contributed additional confirmation of the importance of bilateral activations in language processing, as well as introducing internationally-recognized proficiency testing and standards for the first time as part of the protocol (Andrews et al., 2013; Andrews, 2014).

Few neuroimaging studies address comprehension at the discourse or narrative level across multiple languages. Our current study is one of the first to address listening comprehension and reading comprehension in an ecologically valid way, by presenting normal conversations and authentic texts, instead of pieces of language presented out of context. Research studies need to move toward more realistic language stimuli like narratives (see, for example, Verga & Kotz, 2019). By providing subjects with real-world stimuli, we believe that our results will indicate a more realistic and robust description of language representation and use in the brain.

The research questions guiding this study are as follows:

1. Is fMRI sensitive enough to see salient differences in proficiency in highly advanced bilingual speakers?
2. What is the degree of overlap across languages for bilingual speakers listening to both languages? For bilingual speakers reading both languages?

2. Current Study

The purpose of the current study was to examine the neural correlates of bilingual listening and reading comprehension among highly proficiency Russian-English and Spanish-English speakers. We grouped participants based on proficiency – highest level proficiency (CEFR C2) vs. advanced proficiency (CEFR B2), not on order of acquisition or dominance. We predicted that in both listening and reading comprehension conditions, we would find bilateral neural activation. We also predicted that fMRI is, in fact, sensitive enough to capture activation differences across proficiency levels among highly-proficient bilingual speakers of Russian/English and Spanish/English; there will be overlap in these activation areas for speakers listening to and reading both languages.

2.1 Participants

2.1.1 Spanish/English bilingual participants. Participants were bilingual in Spanish and English. Participants' proficiency in both English and Spanish was determined to be CEFR level B2 or higher based on proficiency testing scores. Spanish/English bilingual participants completed proficiency testing in both languages unless they reported that they completed a graduate-level degree in their L1; in that case, the participant only completed L2 proficiency testing. Participants were divided into two groups based on Spanish proficiency and education level[1]. The first group, Group A, had obtained graduate degrees taught in Spanish (CEFR C2 level), or passed a Spanish proficiency test at the C1 level. The second group, Group B, had at least B2 level proficiency in Spanish. Group A (native or native-like proficiency in Spanish, N=5, 4 females, 1 male) and Group B (advanced proficiency in Spanish, N=4, 2 females, 2 males) completed the experiment.

For Group A, the average age was 34.6 years old (29-47 years, SD=6.47). They had spent an average of 23.8 years (6-34 years, SD=9.6) in a Spanish-speaking country and 10.71 years (0.2-29 years, SD=14.52) in an English-speaking country. Four participants reported that their first language was Spanish, and one reported that her first language was English. For L1=Spanish speakers, the mean age of acquisition of English was 11.5 years old (9-15 years old, SD=2.18), and they had spent between 24-34 years in a Spanish-speaking country and 0.2 to nine years in the US. For the L1=English speaker, the age of acquisition of Spanish was 22 years old, with 39 years in the US and 6 years in Spain.

For Group B, the average age was 22 years old (19-30 years, SD=4.64). They had spent between zero to eight years in a Spanish-speaking country and 14-22 years in the US. Three participants reported that their first language was Spanish, and one reported that his first language was English. The age of acquisition of English for L1 Spanish speakers was between zero to10.5 years old, and they had spent zero to eight years in a Spanish-speaking country and 14-22 years in the US. The age of acquisition of Spanish for the L1 English speaker was between two to three years of age, and he lived 19 years in the US and no time in a Spanish-speaking country.

Table 1. Education information by subject

Subject ID	Languages of education	Highest level of education completed
RUSSIAN GROUP A		
RU01	BA and MA taught in English at US university; PhD taught in English and Russian at US university	PhD
RU06	MA and PhD taught in Russian	PhD
RU07	Bachelor's and Master's taught in Russian/French; PhD taught in English	PhD
RU08	Bachelor's and Master's in Russian in Russia, completing PhD in Russian	Completing PhD
RUSSIAN GROUP B		
RU03	College taught in English and Russian at US university	Completing BA (with Russian coursework)
RU04	College taught in Russian/English at US university	Completing BA (with Russian coursework)
SPANISH GROUP A		
SP01	PhD from Spain	PhD
SP02	PhD from Spain	PhD
SP09	MA from Spain, PhD-English/Spanish	PhD candidate
SP16	PhD in Spanish at US university	PhD
SP17	MA taught in English/Spanish/Portuguese	PhD
SPANISH GROUP B		
SP04	1 year English-speaking college in US, 2 years of AP Spanish in high school, Italian/English courses in college	Completing BA (without college-level training in Spanish)
SP07	2 years English-speaking college in US, no Spanish education, Chinese/English/Portuguese classes in college	Completing BA (without college-level training in Spanish)
SP10	2 years English-speaking college in US, English/Spanish classes in college	Completing BA (with Spanish coursework)
SP14	PhD taught in English, 2 years of college in Spanish-speaking country, Bachelor's degree taught in English	PhD (with college-level coursework)

2.1.2 Russian/English bilingual participants. Participants were bilingual in Russian and English. Participants were divided into two groups based on Russian proficiency and education level. The first group, Group A, had obtained graduate degrees with Russian as the medium of instruction. Group A (native or native-like proficiency (CEFR C2 level) in Russian, N=4, 4 females) and Group B (advanced proficiency in Russian, N=2, 2 males) completed the experiment. Participants who had not completed a college undergraduate degree completed proficiency testing in Russian.

For Group A, the average age was 41 years old (31-59 years, SD=11.25). Participants spent between 11 and 26 years in a Russian-speaking country and between two and 48 in an English-speaking country. Three participants reported that their first language was Russian, and one reported her first language as English. For L1=Russian speakers, the mean age of acquisition of English was four to 14 years of age, and they had spent 14-26 years in Russia and two to eight years in the US. For the L1=English speaker, the age of acquisition of Russian was 17 years old, and she spent 3 to 12 months per year for 36 consecutive years in Russia.

For Group B, the average age was 21 years old (20-22 years, SD=2). They had spent 6 weeks in a Russian-speaking country and 20-22 years in the US. The age of acquisition of Russian was 18-19 years old. Both participants reported learning English as a second language; their first languages were Pennsylvania German and Spanish. They acquired English between 0-1 years of age.

A summary of educational information for each of the subjects can be found in Table 1.

2.2 Experimental design

Participants were volunteers who completed two sessions. The first session was behavioral; it involved proficiency testing and obtaining a linguistic history. Russian proficiency tests were the listening and reading comprehension components of a Russian version of CEFR testing, TORFL/TRKI (Testirovanie russkogo kak inostrannogo) (Andrews, 2014; North, 2000; Sobolev & Nesterova, 2014). Spanish proficiency tests were modified DELE exams available from the DELE website, which were previously administered or practice tests (Instituto Cervantes, n.d.). Participants completed two reading comprehension tasks and two listening comprehension tasks at the B2 or C1 level. The English proficiency test was a modified TOEFL practice test (ETS, 2007), also comprising two reading and two listening comprehension tasks. Pre-scan documentation and interviews included questions about the order and age of acquisition of the languages under study, educational levels and time spent in country.

The imaging experiment was a block design in two runs. The first run was the listening, or auditory, run. The second run was the reading run. The auditory run consisted of 20 seconds of language stimulus followed by ten seconds of musical rain, repeated six times for each language. Musical rain was used as an auditory control condition because it activates the auditory cortex, but activation is distinctive from language processing (for further details about musical rain, see Uppenkamp et al., 2006). Stimuli were English, Spanish, or Russian, and their order was randomized; however, each participant heard the stimuli in the same randomized order. The reading run consisted of 20 seconds of visual language presentation followed by ten seconds of a fixation point (a + symbol), repeated six times for each language. Stimuli were English, Spanish, and Russian, presented in random order. Figure 1 shows a general schematic of the design. For a similar design, see Andrews et al. (2013) and Andrews (2014). Participants were told to indicate if they finished the individual reading passages by pressing a button in the scanner. The post-scan debriefing was an interview and questionnaire, and included questions concerning their overall impression of comprehension in the listening and reading scans and any other comments.

2.2.2 Stimuli. The auditory stimuli were naturalistic conversations between a male and female L1 speaker of the target language, where the English speakers were from the US Midwest, the Spanish speakers were from Colombia, and the Russian speakers were from St. Petersburg. All of the speakers recorded for the auditory stimuli knew each other prior to recording. Each set of speakers was given the same list of topics (in translation) about which to speak, but the conversation was not limited to that list. The conversations were edited using Praat (Boersma & Weenink 2019) to eliminate long pauses or periods of noise and were segmented into files of approximately 20 seconds each. Conversation content was neutral across all languages and focused on everyday topics, and conversational topics were randomized to avoid priming effects. Selected English conversation topics used in the imaging experiment were spending time with friends, holiday food traditions, healthy lifestyles, watching sports, extended family, and teaching careers. Russian conversation topics were pets, restaurants, weather, travel, movies, and extracurricular activities for children. Spanish conversation topics were music preferences, pets, television shows, literature, work travel, and favorite seasons.

The reading passages were approximately 100 words long. The reading passages were taken from online news articles and published books. Some passages were edited to meet the length guidelines. Based on pilot testing, reading content was evaluated as neutral and not highly technical across all languages; content was accessible across different proficiency levels and languages. English reading stimuli included passages about geography, a personal narrative about a favorite teacher, history of holiday traditions, an academic text, a news report about a space mission, and a description of climate engineering. The Russian reading stimuli were passages about geography, cultural events, a critical essay about literature, a semiotics essay, architecture, and a biographical text. The Spanish reading stimuli included passages about history and geology of a lake, a fictional literary narrative, history of holiday traditions, an academic text, a description of water pollution, and a history of astronomy.

2.2.3 MRI acquisition and analysis. Imaging was performed using a GE MR750 3T scanner using an 8-channel head coil. For functional imaging, slices were prescribed parallel to the plane of the anterior and posterior commissure. Functional images were acquired with an EPI sequence, with 64x64 in-plane resolution, a 24cm field of view, and 34 slices, each 4mm thick. A total of 284 time points were acquired in each functional run, with TR=2000ms and TE=30ms.

Anatomical imaging consisted of a T1 weighted FSPGR sequence with 256x256 matrix over a 25.6cm FOV and 162 slices each 1mm thick. A combined T2 and proton density weighted sequence was acquired, with a 256x256 matrix, 25.6cm FOV, and 28, 5mm thick axial slices. Finally, a DTI sequence was acquired, again with a 256x256 matrix over a 25.6cm FOV, covering 69 axial slices each 2mm thick. This diffusion sequence included 26 directions and a b-value of 1000. DTI data was acquired but is not included in the current analysis.

Imaging data was analyzed using FSL 6.00. Single subject (first level) preprocessing was performed for each subject with BET 2.1, MCFLIRT motion correction, interleaved slice timing correction, 5mm FWHM spatial smoothing, highpass temporal filtering, and co-registration to the MNI 152 T1 2mm template. Group-level (third level) analyses were performed with local analysis of mixed effects (FLAME 1+2); Z images were thresholded at the voxel level (Z=2.3), and clusters were corrected for multiple comparisons (p=.05). Reported brain regions were obtained using the Harvard-Oxford Cortical Structural Atlas, Subcortical Structural Atlas, and Cerebellar Atlas in MNI152 space after normalization with FLIRT. We report activation of language greater than control condition here in order to focus on language-specific effects, not effects restricted to listening to auditory stimuli or visual processing.

3. Results

3.1 Listening comprehension

3.1.1 Spanish/English bilinguals. Significant activation areas above threshold for listening comprehension are shown in Table 2. In the English listening comprehension minus musical rain condition, the two groups show differences in activation. For Group A, there is left posterior STG and left posterior MTG activation. Activated regions are shown in Figure 2. For Group B, this includes the right Crus I, Right VI, left planum temporale, and right posterior MTG. Activated regions are shown in Figure 3.

Table 2. Activation for listening comprehension condition for Spanish/English bilinguals

Structure	Voxels	Coordinates	Z-score	*p*	Structure	Voxels	Coordinates	Z-score	*p*
English > Rain					**Spanish > Rain**				
Group A					**Group A**				
Posterior STG (L)	1906	-66, -18, -9.34	13.5	<.001	MTG (temp-occ) (L)	1228	-56, -48, 2	8.87	<.001
Posterior MTG / Posterior STG (R)	1683	64, -22, -6	17.2	<.001	Cerebral white matter (R)	568	60, -14, 0	1.4	0.04
Group B					**Group B**				
Right Crus I / Right VI	6734	32, -66, -26	6.45	<.001	Right Crus I	6755	30, -64, -34	7.09	<.001
Planum temporale (L)	3217	-62, -14, 4	12.5	<.001	IFG (L)	3390	-50, 22, 0	10.3	<.001
Posterior MTG (R)	1818	60, -32, -2	13.5	<.001	Temporal pole (R)	1972	56, 8, -4	8.01	<.001
					Posterior STG / Posterior MTG (R)	1905	62, -10, -8	16.4	<.001
					Supracalcarine cortex (R)	1854	0, -88, 6	5.31	<.001
					Posterior STG / Planum temporale (L)	1601	-62, -22, 4	13.9	<.001
					SFG (L)	1340	-2, 16, 60	8.21	<.001
					Precentral gyrus (R)	665	50, 2, 52	8.52	0.02

In the Spanish listening comprehension minus musical rain condition, there are also differences across groups. For Group A, left temporo-occipital MTG and right cerebral white matter activations are found. Regions of activation are shown in Figure 4. For Group B, Right Crus I, left IFG, right temporal pole, right posterior STG, right posterior MTG, right supracalcarine cortex, left posterior STG, left planum temporale, left SFG, and right precentral gyrus activations are found. Regions of activation are shown in Figure 5.

3.1.2. Russian/English bilinguals. Significant activation areas above threshold for listening comprehension are shown in Table 3. In the English listening comprehension minus musical rain condition, the two groups show differences in activation. For Group A, there is bilateral posterior MTG/STG, right Crus II, and left precentral gyrus activation. Activated regions are shown in Figure 6. For Group B, there is left posterior MTG and right anterior STG/anterior MTG activation. Activated regions are shown in Figure 7.

In the Russian listening comprehension minus musical rain condition, there are also differences across Groups A and B. For Group A, right posterior and anterior STG, left posterior MTG, left Crus I, left amygdala/hippocampus, left precentral gyrus, right SFG, right MFG, and right IFG activations are found. Activated regions are shown in Figure 8. For Group B, left posterior STG and right anterior STG activations are found. Regions of activation are shown in Figure 9.

Table 3. Activation for listening comprehension condition for Russian/English bilinguals

Structure	Voxels	Coordinates	Z-score	*p*	Structure	Voxels	Coordinates	Z-score	*p*
English > Rain					**Russian > Rain**				
Group A					**Group A**				
Posterior MTG / Posterior STG (R)	3591	62, -26, -4	16.8	<.001	Posterior STG / Anterior STG (R)	6094	58, -8, -8	18.9	<.001
Posterior MTG / Posterior STG (L)	3116	-62, -34, -2	13.9	<.001	Posterior MTG (L)	3754	-56, -30, -6	16.7	<.001
Right Crus II	2455	18, -78, -44	11.5	<.001	Left Crus I	3450	-16, -74, -30	9	<.001
Precentral gyrus (L)	554	-50, -4, 44	9.39	0	Amygdala / Hippocampus (L)	1286	-20, -6, -20	4.67	<.001
					Precentral gyrus (L)	575	-50, -2, 50	11.2	0
					Superior frontal gyrus (R)	547	6, 18, 62	8.06	0
					MFG (R)	500	52, 16, 46	8.27	0
					IFG (R)	491	56, 28, 10	12.2	0
					IFG (R)	431	-56, 24, 8	7.04	0.01
Group B					**Group B**				
Posterior MTG (L)	2262	-56, -34, -4	14.6	<.001	Posterior STG (L)	1982	-62, -22, -2	15.2	<.001
Anterior STG / Anterior MTG (R)	1599	58, -4, -14	13.8	<.001	Anterior STG (R)	1507	58, -4, -12	12.1	<.001

3.2 Reading comprehension

3.2.1 Spanish/English bilinguals. Significant activation areas for reading comprehension are shown in Table 4. Results for the English minus rest condition for Group A speakers show left occipital fusiform gyrus and left temporal pole activation. Regions of activation are shown in Figure 10. For Group B, left occipital pole, left IFG, right precentral gyrus, right MFG, left precentral gyrus, and left MFG activations are found to be significant. These regions are shown in Figure 11.

In the Spanish minus rest reading comprehension condition, Group A speakers show left occipital pole and left posterior MTG activation. Regions of activation are shown in Figure 12. Group B shows right occipital pole, right lingual gyrus, left SFG, and left temporal pole activation. These regions are shown in Figure 13.

3.2.2. Russian/English bilinguals. Significant activation areas for reading comprehension are shown in Table 5. Results for the English minus rest condition for Group A show left occipital fusiform gyrus, left precentral gyrus/MFG, and right precentral gyrus/IFG activation. These regions are shown in Figure 14. For Group B, right cerebral cortex/occipital fusiform gyrus, left posterior MTG, left precentral gyrus/MFG, and right postcentral gyrus activations are found to be significant. These regions are shown in Figure 15.

Table 4. Activation for reading comprehension condition for Spanish/English bilinguals

Structure	Voxels	Coordinates	Z-score	*p*	Structure	Voxels	Coordinates	Z-score	*p*
English > Rest					**Spanish > Rest**				
Group A					**Group A**				
Occipital fusiform gyrus (L)	3864	-24, -88, -20	20.2	<.001	Occipital pole (L)	3794	-8, -94, -18	19.5	<.001
Temporal pole (L)	914	-54, 10, -20	6.32	0	Posterior MTG (L)	1088	-50, -42, -2	8.01	<.001
Group B					**Group B**				
Occipital pole (L)	11003	-10, -94, -6	20.1	<.001	Occipital pole / Lingual gyrus (R)	15614	8, -92, -4	24.9	<.001
IFG (L)	698	-52, 22, 14	8.67	0.01	SFG (L)	4368	-8, 8, 70	14.4	<.001
Precentral gyrus / MFG (R)	539	42, 0, 48	9.38	0.03	Temporal pole (L)	1846	-54, 16, -14	10.1	<.001
Precentral gyrus / MFG (L)	493	-44, -2, 60	9.31	0.05					

In the Russian minus rest reading comprehension condition, Group A shows left occipital pole, left cerebral cortex/hippocampus, bilateral precentral gyrus, right anterior MTG, left temporal pole, Vermis IX/Right IX, and left frontal pole activation. These regions are shown in Figure 16. Group B shows right occipital, left posterior STG, right Crus II/Right VIIb, left lateral occipital cortex, and left supplementary motor cortex activation. These regions are shown in Figure 17.

Table 5. Activation for reading comprehension for Russian/English bilinguals

Structure	Voxels	Coordinates	Z-score	*p*	Structure	Voxels	Coordinates	Z-score	*p*
English > Rest					**Russian > Rest**				
Group A					**Group A**				
Occipital fusiform gyrus (L)	5974	-28, -88, -16	18.3	<.001	Occipital pole (L)	7074	-16, -98, 2	22.2	<.001
Precentral gyrus / MFG (L)	882	-50, -2, 52	7.89	<.001	Cerebral cortex / Hippocampus (L)	3057	-26, -30, -6	6.88	<.001
Precentral gyrus / IFG (R)	736	52, 10, 28	6.48	0.003	Precentral gyrus (L)	2922	-50, -2, 52	9.9	<.001
					Precentral gyrus (R)	2499	48, -2, 42	7.27	<.001
					Anterior MTG (R)	1274	64, 2, -16	7.31	<.001
					Temporal pole (L)	1263	-52, 6, -26	7.75	<.001
					Vermis IX / Right IX	729	2, -58, -44	6.9	0.001
					Frontal pole (L)	478	-6, 56, 44	5.37	0.014
Group B					**Group B**				
Cerebral cortex / Occipital fusiform gyrus (R)	7592	12, -90, -18	19.5	<.001	Occipital pole (R)	7291	6, -98, -6	20.7	<.001
Posterior MTG (L)	2632	-56, -40, -2	12.4	<.001	Posterior STG (L)	5328	-62, -18, -2	14.1	<.001
Precentral gyrus / MFG (L)	1161	-38, -4, 54	8.99	<.001	Right crus II / Right VIIb	767	8, -72, -34	7.16	<.001
Postcentral gyrus (R)	1155	16, -44, 78	5.36	<.001	Lateral occipital cortex (L)	626	-30, -74, 46	15.2	0.002
					Supplementary motor cortex (L)	535	-4, 0, 66	14.2	0.007

4. Discussion and Conclusions

This study is the first to use language proficiency as a means of comparing neural activation in highly-proficient (B2 to C2) groups. It is also the only to use both Russian and Spanish speakers. Results from the current study show bilateral activation, as is standard in modern, 21^{st}-century models of language, for both listening and reading comprehension across two languages. There was overlap of significant activation[3] across languages in each group (where Group A was native/native-like proficiency [C2] and Group B was advanced proficiency [B2]). Our findings of activation in each language and condition are (1) consistent with previous literature on listening and reading comprehension (cf. Price 2010, Schirmer et al. 2012), (2) include additional findings on subcortical and cerebellar activations, and (3) strengthen the previous studies by analyzing groups based on CEFR-level proficiency.

It is relevant to note that the meaning and interpretation of activations acquired in fMRI are the topic of frequent discussion (cf. Gusnard & Raichle, 2001, pp. 689; Cabeza et al., 2001; Bookheimer, 2002, pp. 151-188; Paradis, 2004, pp.154). Challenges in understanding activations are associated with a variety of issues, including differences found in baselines, thresholds, smoothing, subject strategies and response styles, and the tasks themselves. See Andrews (2014) for a discussion of these issues.

In the listening condition, for the language with native/native-like proficiency, we see activation bilaterally in the MTG, right STG, right MFG, right IFG, and some subcortical regions. These findings are consistent with previous studies of listening comprehension (Price, 2010). Bilateral MTG activation has been implicated in semantic systems (Binder et al., 2009; Specht, 2014) and sentence comprehension (Humphries et al., 2001). Other studies of auditory narrative comprehension have also found bilateral MTG, right STG, right MFG, and right IFG activation, as well as activation of the amygdala and hippocampus (AbdulSabur et al., 2014; Babajani-Feremi, 2017; left MTG activation, Mazoyer et al., 1993). This pattern of activation is found for sentences in the right MTG and right STG (Humphries et al., 2001) and speech relative to noise in the left MTG and bilateral hippocampus (Rodd et al., 2010).

The activation patterns in the reading scans confirmed what has been found in previous studies of written language comprehension (Spitsyna et al., 2006; Vigneau et al., 2011). As in other studies of narrative reading comprehension, activation was found in the left IFG, left posterior MTG, right MTG, left (pre-)SMA, and right occipital pole, right lingual gyrus (Ferstl et al., 2008; Henderson et al., 2015; Miura et al., 2005; Moss et al., 2011; Spitsyna et al., 2006; Yarkoni et al., 2008).

The cerebellar activation found in listening comprehension is interesting. Our analyses revealed mainly, but not exclusively, right cerebellar activation. The role of the cerebellum in language processing continues to be an important topic of research of the last two decades, including studies that cite its importance for language functions for non-typical or disordered language (e.g., Ackermann et al., 2007; Hodge et al., 2010; Marien et al., 2001). For example, cerebellar injury can lead to verbal and semantic fluency impairments (Neau et al., 2000; Richter et al., 2007; Schweizer et al., 2010). Some studies have begun to investigate the role of the cerebellum in language processing, citing its activation along with the basal ganglia and putamen (Booth et al., 2007; McAvoy et al., 2016). The cerebellum may also be involved in internal rehearsal (Sokolov et al., 2017), which could be a strategy used in language comprehension (Zekveld et al., 2006). In fact, cerebellar activation has been postulated to be involved with inner speech or verbal rehearsal even without motor activity (Frings et al., 2006; Stoodley et al., 2012).

This study further supports a bilateral model of language representation in the brain. We found significant regions of activation bilaterally, not just the left hemisphere. Importantly, we found bilateral activation for both listening and reading conditions in our study. Our findings are consistent with contemporary models of language representation as outlined by Hickok and Poeppel (2004, 2007, 2015) and others (e.g., Andrews et al., 2013; Hernandez et al., 2001; Huth et al., 2016; Lerner et al., 2011; Schirmer et al., 2012).

Returning to our research questions, we address differences in activation based on language proficiency and the degree of overlap across languages for bilingual speakers. In this first data set in our study series, there are significant differences between Groups A vs. Groups B within the Russian and Spanish groups, but there is greater overlap between the Group A participants of Russian and Spanish for both the listening and reading conditions. These results are in keeping with the literature on processing of multiple languages in the brain (Abutalebi et al. 2013, 2016; Andrews et al. 2013, Andrews 2014). As more data is collected and processed at multiple levels, the analysis will continue to explore differences or overlap in activation in relation to language proficiency in the bilingual and multilingual participants.

There is a larger degree of overlap for speakers within a language group when listening to both target languages (Spanish-English or Russian-English) than for speakers reading both target languages. For Spanish-speaking Group B, there were two structures that activated across listening to both English and Spanish (Right Crus I and left planum temporale). For Russian-speaking Group A, there were three structures activating across both English and Russian listening (right posterior STG, left posterior MTG, and left precentral gyrus). For Russian-speaking Group B, there was one structure activated across both English and Russian listening (right anterior STG).

For the reading condition, only Russian-speaking Group A participants share non-occipital lobe structures across both English and Russian reading (bilateral precentral gyrus). These shared areas of activation further contribute to the concept of different languages using shared structures and language networks in the brain. The reading tasks in the scan were completed within the presentation time based on button box response by two of the participants in Groups A (Russian-English) in all six passages across all languages, and in Group B (Spanish-English) by two participants in 3-5 passages for English. Andrews et al. (2013) results showed, using a regression analysis, that reading speed in the L1 may serve as an indicator of reading proficiency achievement in an L2 (Andrews, 2014).

A consideration for the study is the grouping of participants. We grouped participants based on non-essentialist categories defined by empirical data based on proficiency and education levels in the target languages. Other groupings of participants are possible, for example, by age of acquisition or by L1. While the grouping we have here is important for general observations, it is important to remember that individual differences in language processing can and do occur. Additionally, while all participants were highly proficient in both English and Spanish, or English and Russian, there may remain differences in proficiency across different modalities of the two languages within groups (see Table 1).

The current study provides additional evidence of the important interrelation of neural mapping of first and second languages in the brain. While high language proficiency was a requirement for participation in the study, results show both similarities and differences in language network processing across languages and tasks, which further supports the important role language proficiency in neural activation. Finally, the results here confirm bilateral language processing in the brain.

5. Future Directions

It is important to note that the data presented here are a subset of continuous data collection; recruitment is ongoing for other multilingual subjects. Future studies will address anatomical connectivity in multilinguals (DTI), as well as resting state connectivity to contribute to the growing body of evidence about multimodal language networks. A larger data set will allow us to further elucidate these networks, including variability across individuals, the role of subcortical regions in language networks, and dynamic properties of language processing in the brain.

Notes

[1]Based on Council of Europe level descriptions and testing conducted during the study, the Group A Spanish and Russian participants, all of whom have a PhD or are a PhD candidate, are the equivalent of C2. The description of C2 mastery includes the ability “to deal with material which is academic or cognitively demanding, and to use language to good effect at a level of performance which may in certain respects be more advanced than that of an average native speaker” (Exam English, 2019, paragraph 6). In contrast, C1 proficiency is characterized as “the ability to communicate with the emphasis on how well it is done, in terms of [appropriateness], sensitivity and the capacity to deal with unfamiliar topics” (Exam English, 2019, paragraph 7).

[2]For more information on fMRI and white matter activation, see Gawryluk et al. 2014 and Huang et al. 2018.

[3]Gusnard and Raichle (2001, pp. 689) suggest differentiating between "functionally active" and "activated." Bookheimer focuses on the range of factors that affect resulting scan activations: “Differences observed in the MRI signal between two cognitive states are therefore relative, and

consequently, results from activation imaging experiments depend on skill with which one designs both the experimental and control task… The term *activation* implies only relative changes in MRI signal intensity" (Bookheimer, 2002, pp. 153-54).

Acknowledgements

Special thanks to Syam Gadde (Duke-UNC Brain Imaging Analysis Center) and Andrew Michael (Duke Institute for Brain Sciences) for their guidance in data analysis. We would also like to thank Alexander Cherches and Devika Nephade for their work on the atlas mappings.

Funding: This research was supported by Duke University and the US Department of Education, LRC Grant, CFDA 84.229A.

Conflict of Interest: None to report.

Author Statement: All authors contributed equally to this work and are listed in alphabetical order.

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