Neural Activation in Bilinguals and Monolinguals during a Word-Recognition Task

by

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Abstract

The purpose of this study was to investigate speech recognition among Spanish-English bilingual and English monolingual individuals and to examine blood-oxygenation changes in the prefrontal cortex during the speech recognition task.

Twenty-six English-speaking monolingual adults and 10 fluent Spanish-English speaking bilingual adults participated in the study. All participants completed a gating task incorporating monolingual sentences and code-mixed Spanish-English sentences while wearing a functional near-infrared spectroscopy (fNIRS) band to measure changes in blood-oxygenation.

Bilinguals performed equally well to monolinguals when identifying words in both monolingual and code-mixed sentences. Monolinguals identified English words in monolingual sentences more quickly than English words in code-mixed sentences and more quickly than Spanish words in both code-mixed and monolingual sentences. Spanish-English bilinguals were quicker than monolinguals to identify words with voiced initial consonants. All participants were quicker to identify words with CV-tense structure than CV-lax structure. Monolinguals showed higher levels of blood oxygenation than bilinguals when identifying words with voiced initial stop consonants. All participants displayed higher levels of blood oxygenation when identifying CV-lax words than CV-tense words.

Results suggest that bilinguals are capable of native-like proficiency, with word-recognition capabilities and brain functioning similar to monolinguals when identifying English words. Bilinguals may also be more sensitive to voice onset time for both Spanish and English words.

Chapter 1: Literature Review

In an ever more globally connected world, bilingualism is the norm. Most researchers estimate that at least half of the world's population is fluent in more than one language (Ansaldo, Marcotte, Scherer, & Raboyeau, 2008; De Bot, 1992). Even in the United States, which is sometimes perceived as more monolingual than the rest of the world, a growing number of individuals are fluent in both Spanish and English (Macias, 2014). Moreover, it is increasingly unlikely that those who are fluent in only one language have not had some modicum of exposure to one or more non-native languages. Thus, it is important to consider not only monolinguals but also bilinguals in speech and language research.

Bilingual Language Development

Language development begins early in life. From at least three months of age, infants are attuned to speech sounds, able to differentiate speech from other vocalizations (Molnar & Sebastian-Galles, 2014). Before eight months, infants can detect speech sounds from all world languages; afterwards, infants become specialized in the sounds of languages that only they hear (Kuhl, Ramirez, Bossler, Lin, & Imada, 2010). Between the ages of 12–18 months, infants are better at identifying actual words than possible words from a stream of language sounds (Marchetto & Bonatti, 2013), indicating that infants become attuned to a specific language quite early. Learning more than one language influences the overall acquisition of language and cognitive skills. In the instance of bilingualism, the presence of two languages can have both positive and negative influences on developing language systems. When positive, the influence of the second language (L2) upon the first or native language (L1) is referred to as transference

(Perez & Berlanga, 2015). For example, plosive sounds such as /p/, /b/, and /t/ occur frequently both in Spanish and in English, and readily transfer from L1 to L2.

However, not all speech sounds occur in all languages. Sounds that do not immediately transfer from L1 to L2 are referred to as language interference (Brown, 1998). For example, the Spanish trill sound /R/ is not present in English, and is often difficult for English speakers to acquire. Likewise, English "th" sounds, /ð/ and /θ/ do not occur in Western hemisphere Spanish and are difficult for Spanish speakers to acquire. In such cases, Goldstein and Brunta (2011) explain that a speaker will likely substitute these L2 sounds with the closest available approximation from L1. To give an example, the English word "this" would become "dis." This raises the question of whether acquiring a second language negatively impacts first language learning. Bilingualism can be acquired one of two ways; either from birth at the same time as L1 (simultaneous bilingualism) or after L1 has been established to a certain degree (sequential bilingualism) (Castilla, Restrepo, & Perez-Leroux, 2009). Language transference and interference may be observed in both simultaneous and sequential bilinguals (Bialystok, Craik, Green, & Gollan, 2009). This is not to say, however, that bilingual language learning has a definitively negative impact on language development.

For example, McCarthy, Mahon, Rosen, and Evans (2014) found that while bilingual children show less consistency in word recognition for English than their monolingual counterparts between the ages of 46–57 months, by the time children begin primary school this difference disappears and both groups have a comparable vocabulary size. Other research has shown that sequential bilingual learners are similar to monolingual learners in terms of overall language skill acquisition (Castilla et al., 2009), and that neither simultaneous nor sequential bilingualism causes speech-language disorders (Korkman et al., 2012; Marinis & Chondrogianni, 2011). Furthermore, both simultaneous and sequential bilingual speakers are capable of native-like proficiency (MacLeod & Stoel-Gammon, 2005; McCarthy et al., 2014), indicating that any second language attained is not always inferior to first language abilities. However, bilinguals and monolinguals are not identical in how they process and produce language. Kupisch, Lein, Barton, Schroder, Stangen, and Stoehr (2014) also assert that native-like proficiency is most common in bilinguals who use L2 often over a sustained period of time. Thus, it is more likely that factors such as sensitive periods for language learning, how early L2 is acquired, and the amount of time spent using a language directly affect levels of proficiency in L1/L2, regardless of whether L2 learning is sequential or simultaneous (Castilla et al., 2009; Kupisch et al., 2014; MacLeod & Stoel-Gammon, 2005).

Critical Period vs. Sensitive Periods of Language Learning

Made popular by Lenneberg (1976), the critical period hypothesis of language acquisition states that primary language acquisition after the onset of puberty is extremely difficult. Other researchers (Snow & Hoefnagel-Hohle, 1978) have extended this concept to second language learning, stating that acquiring grammatical knowledge of and spoken proficiency in L2 becomes much more difficult after the critical period of language learning. While there is evidence to refute the idea of a single and fixed critical period (i.e., language development stopping and plateauing at or around puberty) (Granena & Long, 2012; Huang, 2013), it is more likely that there are discrete sensitive periods for language learning which are not fixed but are optimal windows of time for learning for different aspects of language. Thus, language learning, including second language acquisition, is not a skill that is mastered all at once, but rather a collection of skills that are best acquired at certain ages.

Among the evidence refuting a single critical period, particularly for acquisition of L2 grammar, is research by Huang (2013). Chinese-English bilingual speakers were assessed for speech production and grammatical understanding of L2. Controlling for factors such as length of residence (LOR) in an L2 language environment and educational status, Huang (2013) found that early L2 learning onset was associated with greater proficiency in producing L2 speech sounds. However, grammatical understanding of L2 was not associated with age of onset (Huang, 2013), such that an understanding of L2 grammar was displayed by participants who acquired L2 across a range of ages from early childhood to adulthood. Further evidence against a single critical period for language learning is put forth by Brice and Brice (2008), wherein data collected from Spanish-English bilingual individuals' performance on a word-identification gating task revealed that exposure over a long period of time (i.e., 6-15 years) produced the greatest abilities in L2 word recognition. More importantly, participants between the ages of 9 and 15 years showed the greatest proficiency in recognizing speech sounds (Brice & Brice, 2008). This evidence stands in direct contrast to the critical period hypothesis, and suggests that high proficiency with L2 is not totally dependent upon early age of L2 acquisition.

Yet sensitive periods for certain aspects of language do exist. Many researchers accept that there are likely sensitive periods for the acquisitions of language features such as syntax, or how words are combined into phrases (Granena & Long, 2012), and phonology, or the makeup of individual speech sounds (Norrman & Bylund, 2016; Sebastian-Galles, Echeverria, & Bosch, 2005; Skeide, 2014). For example, Norrman and Bylund (2016) found evidence for an early sensitive period for phonology in that attrition of L1, as seen in international adoptees, did not improve L2 phonology. Norrman and Bylund (2016) hypothesized that if acquisition of a second language is hampered by interference from the first language, then adoptees (with L1 attrition) should outperform immigrants (with no L1 attrition), but not native speakers in discriminating between true and subtly modified L2 words. However, no differences were observed between the adoptee and immigrant group. Both groups performed significantly worse than the native-speaker group. Norrman and Bylund (2016) suggest that these findings were due to developmental age influencing phonological acquisition; absence of L1 was not a factor. Therefore, it is important to consider the contributions of age of L2 acquisition and length of time spent regularly encountering L2 to differences between bilingual and monolingual speech perception and production.

Age of Acquisition, Length of Residence, and L2 Proficiency

Two estimates of length of exposure to L2 are age of acquisition (AoA) and length of residence (LoR). Age of acquisition (AoA) refers to the age at which L2 is first encountered, while LoR refers to the amount of time spent in contact with L2. Age of acquisition and LoR are used to make distinctions regarding when a second language is learned, i.e., early, middle, and late bilingualism. While estimates vary somewhat within the literature, Brice and Brice (2008) state that early bilingualism can be taken to refer to L2 onset between 1–8 years, middle bilingualism to onset between 9–15 years, and late bilingualism to onset between 16–22 years. The study of speech perception and production through the lens of AoA and LoR offers behavioral data on ways that bilinguals differ from monolinguals.

Granena and Long (2012) offer a detailed picture of how different aspects of language learning are impacted by both AoA and LoR. As discussed earlier, knowledge of common word sequences (lexical and collocational knowledge) for L2 likely develops across the lifespan, while knowledge of grammar structures (morphosyntax) and individual speech sounds (phonetics) seem to have sensitive periods between 6 years and mid-adolescence and 6–12 years, respectively (Granena & Long, 2012). This is evidenced by the fact that across a battery of language mastery tests, those who acquired L2 after the upper limit of the sensitive period for phonetic skills (12 years of age) displayed much greater proficiency with morphosyntax than with producing and identifying individual speech sounds (Granena & Long, 2012). Thus, LoR may have more of an impact on the ease with which an individual can converse in L2, while AoA may have more of an impact on how individual speech sounds are processed.

The findings of Granena and Long (2012) corroborate those of DeCarli et al. (2015), who found that consistent and sustained practice of L2 was more important than AoA for achievement of high proficiency in conversational L2. Together, these findings indicate a possibility that, although bilinguals can become highly proficient in the recognition and use of L2 word sequences and grammar structures, there may be fundamental differences from monolingual/native speakers in terms of how phonological elements of speech are processed.

Distinctive Features of Words

Phonological cues, such as distinctive features, help both monolingual and bilingual individuals recognize speech sounds and words. Distinctive features refer to phonetic aspects of words that carry a high functional load, making the word more recognizable. Functional load is tied to distinctiveness (Brown, 1988); a phonetic feature with high functional load is one that contributes greatly to making a word understandable. Distinctive features not only help monolinguals distinguish words from a single-language lexicon of words, but may also help bilinguals distinguish words between known languages. Examples of distinctive features include voicing features of consonants and tenseness of vowels; both are elaborated upon below.

Voicing Features. Voice onset time (VOT) is the duration of time between the release of a stop plosive sound (i.e., /p, b, t, d, k, g/) and the onset of voicing. Sounds can be pre-voiced (voicing occurring before the plosive release and referred to as negative VOT) or post-voiced (voicing occurring after the release and referred to as positive lag) (Ryalls, 1996). An example of a pre-voiced word (in Spanish) is *beso* (kiss); an example of post-voiced word is grasp. VOT lags can be either short or long (see Figure 1).

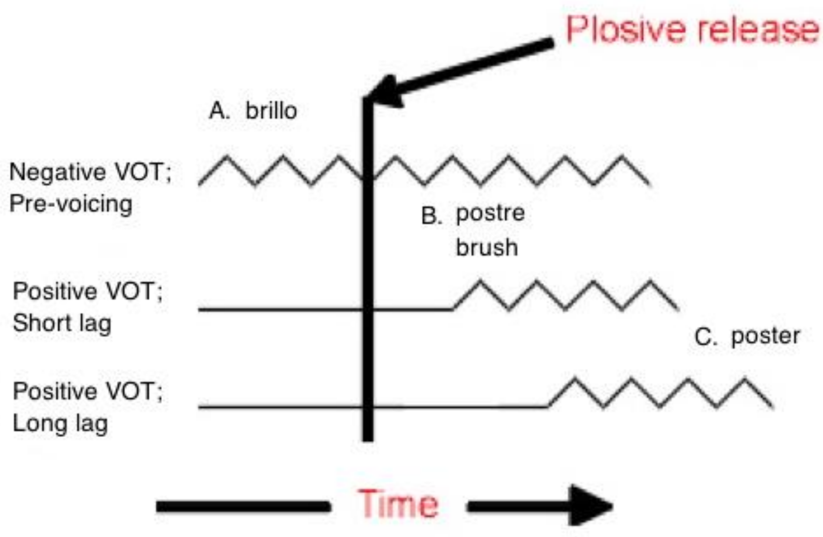

Figure 1. VOT Showing Prevoicing, Short, and Long Lags (Brice & Brice, 2014).

VOT has been used as an acoustic-temporal measure of differences between voiced and voiceless stop consonants (Ryalls, Simon, & Thomason, 2004). For example, voiceless stop consonants /p/, /t/, /k/ have a short lag of less than 20 milliseconds (ms) in Spanish (e.g., *problema*) but a longer lag of 60 ms or more in English (e.g., problem); voiced stop consonants /b/, /d/, /g/ have a VOT of -20 to 0 ms (pre-voicing) in Spanish (e.g., *brillo*), but a VOT of 30 ms or more (post-voicing) in English (e.g., brick) (Balukas & Koops, 2015; Brice & Brice, 2008; Piccinini & Arvaniti, 2015). Note that Spanish voiceless consonants and English voiced consonants have overlapping VOTs; this creates the potential for interference issues in speech perception and is one of the concerns of the present study.

Vowel Tenseness. In the simplest terms, for the purposes of this study, vowel tenseness may be defined as a quality that distinguishes different types of vowels. Long vowels are classified as tense, while short vowels are classified as lax (Halle, 1977). To give examples, the words “free” and “go” contain tense vowels, while the words “wonder” and “kit” contain lax vowels. Vowel tenseness may help in the identification not only among words in one language, but among words in many languages. For example, lax vowels do not occur in Spanish (Brice & Brice, 2008); this could make it easier for a Spanish-English bilingual speaker to distinguish between words in English and Spanish by immediately ruling out Spanish words once a lax vowel is perceived.

Code-Mixing and Code-Switching

It is quite common for bilingual speakers to use more than one language in their daily interactions. This use of both languages may manifest as code mixing or code switching. Code switching refers to the use of both languages within a single discourse (Li, 1996), usually across sentences. For example, a German-English bilingual speaker might say “Hello there! *Wie geht’s*? (How are you?).” Gumperz (1982) offers an example specific to Spanish, taken from conversation: “She doesn’t speak English, so, *dice que la reganan: ‘Si se les va olvidar el idioma a las criaturas’* (she says that they would scold her: ‘the children are surely going to forget their language’)” (p. 76). Code mixing is the use of two languages within a single sentence (Martin, Krishnamurthy, Bhardwaj, & Charles, 2003). For example, “I like that *kleid* (dress),” or *“Andale pues* (okay, swell), and do come again, mm?” (Gumperz, 1982, p. 77). While code mixing is more syntactically complex than code switching, both are common behaviors among bilingual speakers (Grosjean & Miller, 1994; Heredia & Altarriba, 2001; Li, 1996). Most bilinguals voluntarily engage in code-mixing in natural conversation (Gollan & Ferreira, 2009), and researchers have found that bilinguals code-mix with ease in terms of producing speech sounds (Genesee, 2015; Grosjean & Miller, 1994). Code mixing is not perceptibly more taxing than choosing one language over the other, and may in fact be easier than restricting speech to a single language (Gollan & Ferreira, 2009), even though bilinguals may utilize more cognitive resources to choose which language to use when code mixing as opposed to when speaking in a single language.

Most research to examine code-mixing has focused on the ability of bilingual individuals to produce speech sounds in L1 and L2 (Genesee, 2015; Gollan & Ferreira, 2009; Grosjean & Miller, 1994; Heredia & Altarriba, 2001; Piccinini & Arvaniti, 2015). Fewer studies have focused on how code mixing might affect speech perception in bilingual individuals, particularly in relation to monolingual individuals (Brice, Gorman, & Leung, 2013). Brice et al. (2013) found that bilinguals were faster in recognizing some English speech sounds as compared to Spanish speech sounds, specifically voiceless consonants. However, the phonetic frequency of such sounds may have influenced these results. To give an example, high-frequency words are those that occur often in a language, and are thus more easily recognizable (Metsala, 1997). Therefore, it is possible that voiceless consonants had a high frequency and were more easily recognized by participants (Brice et al., 2013). Additionally, the Spanish speakers in the study were all early bilinguals and may have had more exposure to English than to Spanish. Monolinguals, though, need only deal with the functional load (i.e., the importance of certain features that assist in making language distinctions), phonetic frequencies, and frequency of words in only one language. The distinctive feature of voiced/voiceless carries a high functional load, allowing for distinction of many words in English (Brown, 1988). Functional load is not to be confused with cognitive load. Whereas cognitive load refers to mental effort (Sweller, 1988), functional load refers to distinctiveness (Brown, 1988); a phonetic feature with high functional load is one that contributes greatly to making a word understandable.

Even though code-mixing and code-switching may not feel effortful, it is possible that bilinguals are either expending more cognitive resources or using cognitive resources more efficiently when processing two languages. If it is the case that bilinguals utilize cognitive resources more efficiently than monolinguals when processing input from more than one language, then in accordance with research on the neural efficiency hypothesis (Neubauer & Fink, 2009), neuroimaging during a word recognition task should show a lower level of activation in bilinguals. In order to best consider questions of how language processing in the brain might differ between bilinguals and monolinguals, however, a brief review of language processing models is necessary.

Neural Models of Speech Production and Perception

There is a well-established body of literature regarding the localization of speech processing in the brain. In an early review of research addressing the neurobiology of language, Marin (1976) details the importance of Broca's area, located in the posterior portion of the left inferior frontal gyrus (LIFG) to speech-language functions. While little detail is given, reference is made to the concentration of language processing in the left hemisphere and the presence of both an acoustic-phonetic system for speech perception and an articulatory output system for speech production (Marin, 1976).

One classical model of the neurobiology of language, discussed and refuted by Hagoort (2014), is the Wernicke-Lichtheim-Geschwind (WLG) model. Briefly, Hagoort (2014) outlined the WLG model as involving Broca's area in the LIFG, Wernicke's area in the temporal lobe, and Geschwind's territory in the inferior parietal lobule. Language comprehension and language production involves passage of signals along anterior and posterior language areas; communication between speech centers is facilitated via the arcuate fasciculus, a bundle of fibers connecting temporal language areas to frontal language areas (Fadiga, Craighero, & D'Ausilio, 2009).

It remains accepted as fact that the brain areas detailed above are indeed largely responsible for language. However, many researchers now do not believe Broca's area to be restricted in function to only speech production, nor Wernicke's area only to speech comprehension; it is more likely that all of the aforementioned language centers of the brain are involved both in comprehension and production of speech (Hagoort, 2014; Fadiga et al., 2009). Hagoort (2014) provides an overview of an emerging, dynamic view of speech perception and production, in which speech production and comprehension act as shared networks among frontal, temporal and parietal regions. It is also likely that more areas than just dedicated speech centers are used for language. For example, Hagoort (2014) states that memory processes have been implicated in language processing, as individuals access a mental lexicon of speech sounds and complete words both when listening and when speaking.

Bottom-up, Top-down, and Combination Processing Models

Focusing now specifically on speech perception, let us turn to models of the cognitive processing of language. Bottom-up processing refers to the use of only acoustic-phonetic information, pure sounds stripped of context and other outside knowledge, to identify words (Ryalls, 1996). This acoustic information is crucial for recognizing reduced words, such as those that occur in natural speech (Janse & Ernestus, 2011). However, the less intelligible conversational speech becomes, the more a person must bolster acoustic information with semantic information, thinking of the meaning behind the ambiguous sound. This use of information such as semantic knowledge and prior context constitutes top-down processing (Ryalls, 1996). For example, reduction of a word such as “yesterday” into a sound such as “yeshay” during conversational speech requires a listener to use context to help interpret the ambiguous acoustic information being received (Janse & Ernestus, 2011). Further evidence for the importance of top-down processing in word recognition is presented by Fox and Blumstein (2015). When presenting phonetically ambiguous words such as buy, beginning with */b/* and pie, beginning with */p/*, prior context is strongly influential (Fox & Blumstein, 2015). If a sentence is noun biased (e.g., Mary likes the…) a person is more likely to accurately identify the word pie, and to hear the word “pie” even when the word “buy” is presented (Fox & Blumstein, 2015).

The cohort model. Bottom-up and top-down processes are not entirely separate, however. Most researchers agree that top-down and bottom-up processing happen in combination (Janse & Ernestus, 2011; Marslen-Wilson & Welsh, 1978; Zekveld, Heslenfeld, Festen, & Schoonhoven, 2006). Together, acoustic and semantic information combine to form a complete representation of what is being heard (Marslen-Wilson & Welsh, 1978). Marslen-Wilson (1989) expounded upon this interaction between bottom-up and top-down processing when proposing the cohort model of speech perception. Briefly, the cohort model outlines a process whereby known words form a cohort, and word recognition occurs as a result of eliminating possible candidates for what is being said from the cohort until only the best-fitting option remains (Marslen-Wilson, 1989). This process begins with bottom-up information; for example, eliminating words that do not begin with a /k/ sound. The gathering of acoustic-phonetic information allows for a narrowing down of word possibilities; however, top-down information such as prior context also plays a role (Marslen-Wilson, 1989). For example, after hearing a sentence fragment ending with an article, one may eliminate words that are verbs and primarily selecting nouns, paring down the pool of possible words until a most likely noun candidate emerges. Though not directly stated, Marslen-Wilson's (1989) cohort model suggests that both basic temporal processing and more complex prefrontal processing are occurring. One first hears a sound and then interprets it as meaningful; it is during this interpretation that prefrontal cognitive processes occur.

Gating

One method of investigating the process by which acoustic-phonetic information becomes understandable speech is gating. Developed by Grosjean (1988), gating is a technique wherein an auditory stimulus is presented to a listener in equal and increasing segments of time. The auditory stimulus may range from a single word to a longer phrase or sentence, though the present study is concerned with gating single words. The segments of sound which a listener hears are referred to as gates. Gates are typically presented in segments of about 60-70 ms (Brice, Gorman, & Leung, 2013; Grosjean, 1988; Li, 1996). A listener will hear the first 70 ms of a word, then 140 ms of a word and so on until the listener identifies the word. Delay between each segment varies slightly, as after each segment the listener is asked to give an identification or indicate that the word is not understandable. Typically, two outcome measures are collected; isolation point and recognition point. Grosjean (1996) defines isolation point and recognition points as follows:

1. Isolation point – that is, the size of the segment (measured in msec or % of stimulus) needed to identify the stimulus (without any change in response thereafter).
2. [Recognition point refers to] Confidence rating at various points in time (at isolation point, end of stimulus, etc.) One can also examine the duration of the segment needed to attain (and maintain) a particular rating after isolation. Ratings are used to define points in the stimulus such as the total acceptance point or the "recognition" point. (p. 598)

In the present study, isolation point is defined as the portion of the stimulus (e.g., 10 of 14 gates) needed for participants to make a correct identification of the target word; recognition point refers to the portion of the stimulus needed for participants to give two consecutive, accurate identifications with 100% certainty.

Gating is a useful method of inquiry in that it quantifies the amount of phonetic information needed for a listener to recognize and identify a word (Li, 1996). Sebastian-Galles and Soto-Faraco (1999) employed a gating technique to examine the recognition of non-word phonemic contrasts in Spanish-Catalan bilinguals. All stimuli were disyllabic non-words with phonemic contrasts that were common to Catalan but nonexistent in Spanish. Sebastian-Galles and Soto-Faraco (1999) found that participants with a Spanish L1 required a larger portion of the gated stimuli to make an accurate identification as compared to participants with a Catalan L1. These findings can be taken as support for the hypothesis that L1 impacts the perception of non-native phonemic contrasts, even when L2 exposure is early and extensive.

However, because the perception of individual words rarely happens in isolation, it is important to consider those top-down effects of syntax and prior context upon gated words. A gated word may also be preceded by a stream of speech, as is the case in the present study. In this way, it is possible to examine how factors such as prior context and code-mixing affect how much phonetic information is needed to recognize a word. In the present study, all stimulus words, both English and Spanish, were nouns and all sentences were noun biased to match the type of stimulus word presented.

Gating is also especially suited to bilingual language research as a method of investigating the impact of VOT upon word recognition. Gating provides a method of examining how these VOT time differences (in milliseconds) with voiced and voiceless stop/plosive consonants may affect speech perception in bilinguals and monolinguals. For example, one might expect VOT to affect what proportion of the initial consonant in a word is required for recognition.

Gating can also be used in studies focused on practical, clinical applications. For example, Montgomery (1999), through a gating study, found that children with specific language impairments needed no more acoustic-phonetic information to identify words than their normally-developing peers. This could be due to deficits not arising until later in the speech perception process, but the results could also be explained by the fact that the stimuli included only familiar mono-syllabic words (Montgomery, 1999). Gating studies that employ words with lower frequency and/or words with more syllables might produce different results. Also important to consider, both for general knowledge and clinical application, are the cognitive processes occurring in the brain while phonetic information is being processed. Thus, gating techniques may be augmented by neuroimaging techniques to provide a more complete understanding of speech perception.

Neuroimaging Investigations of Bilingual Language Perception and Production

Earlier, neurobiological models of language were discussed (Fadiga et al., 2009; Hagoort, 2014; Marin, 1976). However, potential differences between monolingual and bilingual language processing were not explored. Abutalebi, Cappa, and Perani (2001) presented evidence that L2 processing occurs in the same dedicated language areas as L1. Questions were raised regarding possible bilingual-monolingual differences in recruitment of other brain areas, such as the prefrontal cortex, for language processing, particularly when bilingual individuals switch between multiple languages as with code-mixing or code-switching (Abutalebi et al., 2001). In a later review of functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) studies, Abutalebi (2007) explored evidence for such differences, finding that many studies supported the notion of increased brain activity in areas also associated with L1 language processing as bilinguals engaged in both code-switching and code-mixing. There is also a wealth of evidence for the recruitment of additional areas by bilingual language users when engaging in code-mixing and code-switching; specifically, the left prefrontal cortex, anterior cingulate cortex (ACC), and basal ganglia (Abutalebi, 2007; Kovelman, Shalinsky, Berens, & Petitto, 2014; Jasinska & Petitto, 2013; Hernandez, Dapretto, & Bookheimer, 2000).

Exploring differences not only between monolinguals and bilinguals but among bilinguals themselves, Hernandez (2009) conducted an investigation into differences in levels of neural activation between low-proficiency and high-proficiency bilinguals.

When given a picture-naming task, bilinguals showed increased dorso-lateral prefrontal cortex (DLPFC) when switching between languages as opposed to naming pictures in a single language, regardless of whether proficiency level was low or high. Activation was also noted in brain areas devoted to memory and somatosensory processing (e.g., the hippocampus and amygdala) in both language switching and single-language conditions (Hernandez, 2009). It is unclear, however, if this activation is unique to bilinguals or if it is shared with monolinguals.

Although Hernandez's (2009) work addressed only early and late bilinguals, evidence from Archila-Suerte, Zevin, and Hernandez (2015) supports the idea that neural processing both overlaps and differs between bilinguals and monolinguals and between early and late bilinguals. In an fMRI study of brain activity during both speech production and speech perception tasks, it was found that monolinguals, early bilinguals (those with an AoA of less than 9 years old), and late bilinguals (those with an AoA of more than 10 years old) performed similarly in terms of behavioral results for production and perception of speech sounds in L2 (L1 for monolinguals). However, neural processing of speech sounds did differ. Early bilinguals showed greater engagement of prefrontal regions involved in working memory compared to monolinguals, while late bilinguals showed greater activation in the inferior parietal lobule compared to both early bilinguals and monolinguals (Archila-Suerte et al., 2015). Similarly, Perani et al. (1998) found evidence for differences in activation in both left and right temporal and hippocampal regions between high and low proficiency groups in a PET investigation of performance on a task involving comprehension of an entire story. Low proficiency bilinguals showed lower activation than high proficiency bilinguals, though both bilingual groups displayed greater activity (more blood flow) located in areas also associated with L1 (Perani et al., 1998). Together, this evidence suggests that although general localization of neural speech processing may be common between monolingual and bilingual groups, levels of activation may differ. This supports the notion that the cognition underlying language comprehension differs between bilingual and monolingual individuals.

Functional near infrared spectroscopy (fNIRS), a technique which uses infrared light to examine hemodynamic response in a shallow brain depth (approximately 3cm), is an emerging method of investigating levels of neural activation. Recently, researchers have begun to investigate bilingualism utilizing fNIRS technology (Kovelman, Shalinsky, Berens, & Petitto, 2008; Kovelman et al., 2014; Jasinska & Petitto, 2013; Zinszer, Chen, Wu, Shu, & Li, 2015). Even though some fNIRS studies have focused specifically on phonetic perception (Zinszer et al., 2015), there is no current evidence of research that combines neuroimaging investigations of bilingualism with Grosjean's gating paradigm, which is particularly suited to examining the effects of phonetics upon speech recognition. This could be because there is a delay between response to a stimulus and peak oxygenation readout on the fNIRS device (Tak & Ye, 2014). Perhaps to compensate for this, most fNIRS researchers (Minagawa-Kawai, Mori, Naoi, & Kojima, 2007; Kovelman et al., 2008; Zinszer et al., 2015) have employed block designs, where peak oxygenation levels during blocks of time starting approximately 5 seconds after the initial presentation of target stimuli are measured against a baseline of oxygenation data. The present study could therefore add valuable new information to the field by combining two methodologies to examine phonetic elements of bilingual speech perception in a novel way.

The Current Study

The aim of the present study is to investigate neural activation during a code-mixed word recognition task in both English monolingual and Spanish-English bilingual individuals, with special attention to the phonetic features of these words. Incomplete simple sentences will be presented to listeners, followed immediately by a gated target word to recognize. Words will be either matched to the sentence language or code-mixed. Words are also classified into different phonetic conditions as having either voiceless consonants (with a VOT of 0 or below) or voiced consonants (with a VOT of an above 0 value), and either lax vowels (e.g., /ɑ/) or tense vowels (e.g., /ə/).

Several hypotheses are proposed:

1. Bilinguals will be faster (e.g., show earlier isolation points and recognition points) than monolinguals for recognition of code-mixed words, given their access to a larger cohort of potential words.
2. Higher levels of blood-oxygenation are also expected in bilingual individuals when recognizing code-mixed words, given past research demonstrating activation in more brain areas for proficient bilinguals compared to monolinguals in word-recognition tasks (Archila-Suerte et al., 2015; Perani et al., 1998).
3. Monolinguals will show later isolation points and recognition points than bilinguals for voiced consonant trials, given that unlike Spanish, words in English do not have negative VOTs (that is, vocalization occurring before plosive release) (Piccinini & Arvaniti, 2015).

4. Blood oxygenation will be higher in monolingual participants for voiced conditions, given the low prevalence of negative VOT words in English but not in Spanish (Balukas & Koops, 2015; Brice & Brice, 2008; Piccinini & Arvanitit, 2015).
5. Due to the absence of lax vowels in Spanish (Brice & Brice, 2008), bilingual participants will be slower and display higher neural activation when identifying words with lax vowels.
6. Also due to the absence of lax vowels in Spanish (Brice & Brice, 2008), bilinguals will have higher blood-oxygenation levels than monolinguals when identifying lax vowel words.

Chapter 2: Methods

Participants

English monolingual and Spanish-English bilingual adult individuals were recruited for this study. Selection criteria included proficiency in English for monolinguals and both English and Spanish for bilinguals. Those who were bilingual in a different language and those who were proficient in both Spanish and English but spoke more than two languages were excluded. Only persons between the ages of 18 and 46 were recruited for the study. While data was also collected from individuals with mild traumatic brain injury for part of a larger investigation, those individuals were excluded from the present investigation. Individuals were recruited via the research participation program of the author's university.

A total of 35 participants remained in the present study after exclusions based on age, language status, and brain injury status. The study consisted of 25 monolingual participants (20 female and 5 male) and 10 bilingual participants (8 female and 2 male). Participants ranged in age from 18 – 46, with a mode of 20 years of age. Though gender is reported here for the sake of best describing the sample of participants, no gender differences were explored in this study. Prior research (Brice & Brice, 2008; Brice, Gorman, & Leung, 2013) suggests that gender is not an intervening variable in speech perception. Of the 10 bilingual participants, seven reported English as their native language and three reported Spanish as their native language. Although all bilingual participants were proficient in both spoken languages, age of onset for L2 was variable among participants.

Materials

Language proficiency rating. An initial self-report screening questionnaire was given to participants (see Appendix); if all inclusionary criteria were met, then participants scheduled a time to come in-person to the lab. Upon arrival on the study site, participants self-rated their language abilities and were then formally classified as bilingual or monolingual using the International Second Language Proficiency Rating tool (ISLPR; Wylie & Ingram, 1999). This was administered by the principal investigator, a highly proficient Spanish-English bilingual. Participants with an oral proficiency rating of three or higher in both English and Spanish were classified as bilingual; those with a proficiency score below that cutoff in Spanish were classified as monolingual. None of the participants' self-ratings differed by more than one point on the ISLPR; if a participant's self-rating placed them above the threshold for inclusion in the bilingual group but the principal investigator's oral assessment placed them below the threshold for inclusion, the rating of the principle investigator was used.

Physical equipment and software. A Dell desktop computer running E-prime 2.0 was used to present the gating task. The computer was attached to two monitors placed back-to-back. Participants were seated at one monitor and engaged in the experiment. The experimenter was seated directly across from the participant at another monitor. The participant's monitor was attached to both a keyboard and a computer mouse; the experimenter's monitor was attached to a computer mouse. Auditory stimuli were presented through Sennheiser over-ear HD-201S headphones with a frequency response range of 21-18000 Hz and a sensitivity of 108 dB.

Neuroimaging data were collected using a Biopac fNIRS recording box and 16-channel forehead-mounted sensor band. The sensor band contained four infrared light sources and ten detectors. Neuroimaging data were recorded using fNIR Software (Version 3.4; Biopac, 1997). The gating task and language stimuli were presented using a modified version of Grosjean's (1996) gating paradigm, presented to participants in E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA).

Sentence-word stimuli. A total of 5 trial items followed by 60 stimuli were presented, with words ranging from 4 – 14 gates. Each target stimuli was presented at the end of a simple three to four word sentence. The last word in each sentence was the gated target stimulus. All words were nouns, and all sentence-word combinations were spoken by a fluent, female Spanish-English speaker. The speaker used careful articulation and a neutral accent in both Spanish and English. The sentence-word stimuli were taken from prior published studies (Brice & Brice, 2008; Brice et al., 2013).

Forty of the 60 stimuli were code-mixed, containing Spanish and English words; code-mixed stimuli began with a sentence in one language and ended with a target word in the other language (e.g., "I see a *brillo*", "Yo quiero *cheese*"). Nine stimuli were presented entirely in Spanish and 11 were presented entirely in English. Single-language sentences were randomly interspersed among the code-mixed sentences to prevent participants from predicting patterns of code-mixed target stimuli. A full list of stimuli are available upon request. The above construction resulted in four language conditions: English sentence – English word (EE), English sentence – Spanish word (ES), Spanish sentence – English word (SE), and Spanish sentence – Spanish word (SS).

Four phonetic constructions were also used. Target words contained beginning consonant clusters in the following pattern: consonant-consonant-vowel voiced and voiceless (CCV+ voiced, CCV- voiceless). Beginning consonant-vowel clusters were constructed as follows: consonant-vowel tense and consonant-vowel lax (CV tense, CV lax). Note that lax vowels do not regularly occur in Spanish (Delattre, 1965); thus the CV lax condition contained no Spanish stimuli.

Procedure

General procedure. Participants completed the experiment in a quiet university lab. Upon arrival, participants gave informed consent and were evaluated for language proficiency. An explanation of the sequence of events was given by the experimenter; all instructions were given in the primary or preferred language of the participant. Participants were seated at the computer and fitted with the fNIRS band. In order to facilitate fNIRS recording, light levels were dimmed so that only the emergency light remained on in the room. After assuring that participants were comfortable and reiterating that participation in the experiment could be ended at any time for any reason by the participant, the experimenter activated the E-prime gating task and took a seat at the monitor opposite of the participant.

Gating task. Participants were auditorially presented with sentences and gated words. Gated words were presented in approximately 70 ms increments. After each gate, the monitor displayed the questions “Do you recognize the word?”. Participants responded “yes” or “no” via button-press. A response of “no” triggered presentation of the next auditory gate. A response of “yes” prompted participants to name the word. The experimenter used the computer mouse to record the response as correct or incorrect; the participant saw no indication of correctness. After this, the question “Are you 100% sure?” was displayed. Participants responded to this question via button press. Interstimulus interval varied slightly, as presentation of the next auditory gate depended upon the time it took participants to answer the question. Presentation of gated words continued until either all gates were displayed or until a participant gave two correct identifications with 100% certainty, after which the next trial began.

Chapter 3: Results

Data were analyzed in two separate categories: word retrieval results and neuroimaging results. Word retrieval results included data from isolation point (the proportion of the word, e.g., 7 out of 10 gates, needed to make an initial identification), recognition point (the proportion of the word needed to make two consecutive correct identifications with 100% certainty), and the difference between isolation point and recognition point. Neuroimaging results included data from the fNIRS band measuring oxygenated blood levels across the frontal lobe. Oxygenation data for each optode was detrended and processed using fNIRSoft (Biopac®).

Word Retrieval Results

Data Analysis

Isolation point data (the proportion of the word, as measured in 70 ms gates, needed to make an initial identification) was examined using three two-way ANOVAs. The first ANOVA treated language group (bilingual, monolingual) as the between subjects variable and sentence-word condition (English-English, Spanish-Spanish, English-Spanish, and Spanish-English) as the within subjects variable. The second ANOVA treated language group (bilingual, monolingual) as the between subjects condition and consonant voicing features (voiced, voiceless) as the within-subjects variable. The third ANOVA treated language group (bilingual, monolingual) as the between subjects variable and vowel tenseness (tense, lax) as the within subjects condition. The same strategy was then repeated for recognition point data (the proportion of the word, as measured in 70ms gates, needed to elicit two correct verbal identifications with 100% accuracy), and for examining the difference between isolation and recognition point.

Mean values for isolation point and recognition point are to be interpreted as follows: scores can range from null to one, and represent portions of the full word. For example, a value of 1.00 indicates 100% of gated word segments, and a value of 0.5 represents 50% of gated word segments.

Sentence-Word Conditions

Isolation point data. A 2 (language condition) by 4 (sentence-word condition) mixed-models ANOVA was run with isolation point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. The sentence-word condition referred to the four carrier sentence – target word pairs used: English sentences – English words, English sentences – Spanish words, Spanish sentences – English words, and Spanish sentences – Spanish words.

A significant main effect for sentence-word condition was discovered, $F(3, 32) = 11.28$, $p < .001$, $\eta p^2 = .326$. Participants isolated words earlier for English-English sentences ($M = .582$, $SE = .028$) than for Spanish-English sentences ($M = .620$, $SE = .024$), which in turn were isolated earlier than English-Spanish sentences ($M = .632$, $SE = .027$), which in turn were isolated earlier than Spanish-Spanish sentences ($M = .671$, $SE = .029$). Recall that lower values mark an isolation point occurring earlier in the presentation of a word, indicating better performance.

A significant main effect for language group was also discovered, $F(3, 32) = 5.24$, $p = .028$, $\eta p^2 = .134$. Bilingual participants ($M = .567$, $SE = .044$) isolated words earlier than did monolingual participants ($M = .686$, $SE = .027$).

A significant interaction between sentence-word condition and language group was present, $F(3, 32) = 15.83$, $p < .001$, $\eta p^2 = .318$. Refer to Figure 2 for a graph of this interaction. A Fisher's least significant difference (LSD) post hoc test revealed significant differences between bilinguals and monolinguals on Spanish-Spanish sentence-word pairs, such that bilingual participants (*M* = .575, *SE* = .049) required fewer gates than monolingual participants (*M* = .767, *SE* = .030) to make an initial identification of stimulus words, *p* = .002. Bilingual participants (*M* = .549, *SE* = .047) also required fewer gates than monolingual participants (*M* = .715, *SE* = .029) to make an initial identification of stimulus words in the English-Spanish condition, *p* = .005. No differences arose between monolinguals (*M* = .600, *SE* = .030) and bilinguals (*M* = .564, *SE* = .048) for English-English conditions, *p* = .530. Neither did differences arise between monolinguals (*M* = .662, *SE* = .025) and bilinguals (*M* = .577, *SE* = .041) on Spanish-English conditions, *p* = .089.

Among monolingual participants, the number of gates needed to make a correct identification varied significantly for each sentence-word condition, as summarized in Table 1. Words in English-English conditions (*M* = .600, *SE* = .030) were isolated more quickly than words in Spanish-English conditions (*M* = .662, *SE* = .025), English-Spanish conditions (*M* = .715, *SE* = .029), and Spanish-Spanish conditions (*M* = .767, *SE* = .030), *p*s < .001. Words in Spanish-Spanish conditions took longer to isolate than words in English-English conditions, *p* < .001, words in English-Spanish conditions, *p* =.001, and words in Spanish- English conditions, *p* < .001. Words in English-Spanish conditions took longer to isolate than words in English-English and Spanish-English conditions, *p*s <

.001, but a shorter amount of time to isolate than words in Spanish-Spanish conditions, $p = .001$.

Table 1. *Isolation point among monolingual participants for sentence-word conditions*

Sentence – Word pair	Mean	Standard Error
English sentence – English word	.600	.030
Spanish sentence – English word	.662	.025
English sentence – Spanish word	.715	.029
Spanish sentence – Spanish word	.767	.030

*All differences between means are significant at the .001 level

Among bilingual participants, the proportion of the word needed to make an initial identification did not vary between English-English ($M = .564$, $SE = .048$) and Spanish-Spanish ($M = .575$, $SE = .049$) conditions, $p = .679$; between English-English and English-Spanish ($M = .549$, $SE = .047$) conditions, $p = .421$; between English-English and Spanish-English ($M = .662$, $SE = .025$) conditions, $p = .497$; between Spanish-Spanish and English-Spanish conditions, $p = .264$; between Spanish-Spanish and Spanish-English conditions, $p = .924$; nor between English-Spanish and Spanish-English conditions, $p = .152$.

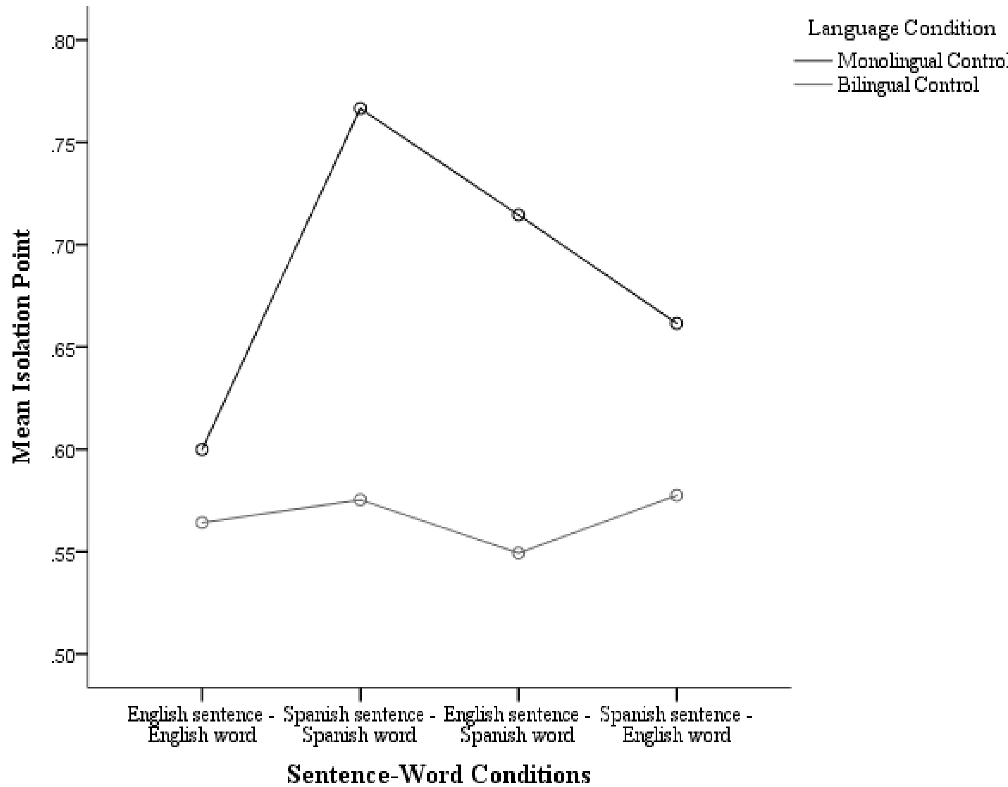

Figure 2. Interaction between language condition and sentence-word condition for isolation point.

Recognition point data. A 2 (language condition) by 4 (sentence-word condition) mixed-models ANOVA was run with recognition point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. The sentence-word condition referred to the four carrier sentence – target word pairs used: English sentences – English words, English sentences – Spanish words, Spanish sentences – English words, and Spanish sentences – Spanish words.

A significant main effect for sentence-word condition was discovered, $F(3, 32) = 17.29$, $p < .001$, $\eta p^2 = .344$. Participants recognized English-English sentences ($M = .841$, $SE = .017$) earlier than Spanish-English sentences ($M = .848$, $SE = .017$), which in turn were recognized earlier than Spanish-Spanish sentences ($M = .894$, $SE = .018$), which were recognized earlier than English-Spanish sentences ($M = .897$, $SE = .016$). Recall that lower values indicate recognition point occurring earlier in the presentation of a word.

No significant main effect for language group was discovered, $F(3, 32) = 3.31$, $p = .078$, $\eta p^2 = .091$. Bilingual participants ($M = .841$, $SE = .027$) recognized words similarly to monolingual participants ($M = .899$, $SE = .016$).

A significant interaction between sentence-word condition and language group was present, $F(3, 32) = 39.99$, $p < .001$, $\eta p^2 = .548$. Refer to Figure 3 for a graph of this interaction. An LSD post hoc test revealed significant differences between bilinguals and monolinguals on Spanish-Spanish sentence-word pairs, such that bilingual participants ($M = .831$, $SE = .031$) required fewer gates than monolingual participants ($M = .957$, $SE = .018$) to make two consecutive correct identifications of stimulus words, $p = .001$. Bilingual participants ($M = .828$, $SE = .027$) also required fewer gates than monolingual participants ($M = .965$, $SE = .016$) to make two consecutive correct identifications of stimulus words in the English-Spanish condition, $p < .001$. No differences arose between monolinguals ($M = .817$, $SE = .018$) and bilinguals ($M = .865$, $SE = .030$) for English-English conditions, $p = .175$. No differences arose between monolinguals ($M = .856$, $SE = .030$) and monolinguals ($M = .841$, $SE = .029$) for Spanish-English conditions, $p = .651$.

Among monolingual participants, the number of gates needed to make two consecutive correct identifications varied significantly, as depicted in Table 2. Words in English-English conditions ($M = .817$, $SE = .018$) were recognized more quickly than words in Spanish-English conditions ($M = .856$, $SE = .017$), Spanish-Spanish conditions ($M = .957$, $SE = .018$), English-Spanish conditions ($M = .965$, $SE = .016$), ps $< .001$. Words in Spanish-Spanish conditions took longer to recognize than words in English-

English conditions, $p < .001$, and words in Spanish- English conditions, $p < .001$, but not words in English-Spanish conditions, $p = .311$.

Table 2. *Recognition point among monolingual participants for sentence-word conditions*

Sentence – Word pair	Mean	Standard Error
English sentence – English word	.817	.018
Spanish sentence – English word	.856	.017
Spanish sentence – Spanish word	.957	.018
English sentence – Spanish word	.965	.016

*All differences between means are significant at the .001 level

Among bilingual participants, the proportion of the word needed to make two consecutive correct identifications did not vary between English-English ($M = .865$, $SE = .030$) and Spanish-Spanish ($M = .831$, $SE = .031$) conditions, $p = .105$; between English-English and English-Spanish ($M = .828$, $SE = .027$) conditions, $p = .058$; between English-English and Spanish-English ($M = .841$, $SE = .029$) conditions, $p = .113$; between Spanish-Spanish and English-Spanish conditions, $p = .831$; between Spanish-Spanish and Spanish-English conditions, $p = .605$; nor between English-Spanish and Spanish-English conditions, $p = .438$.

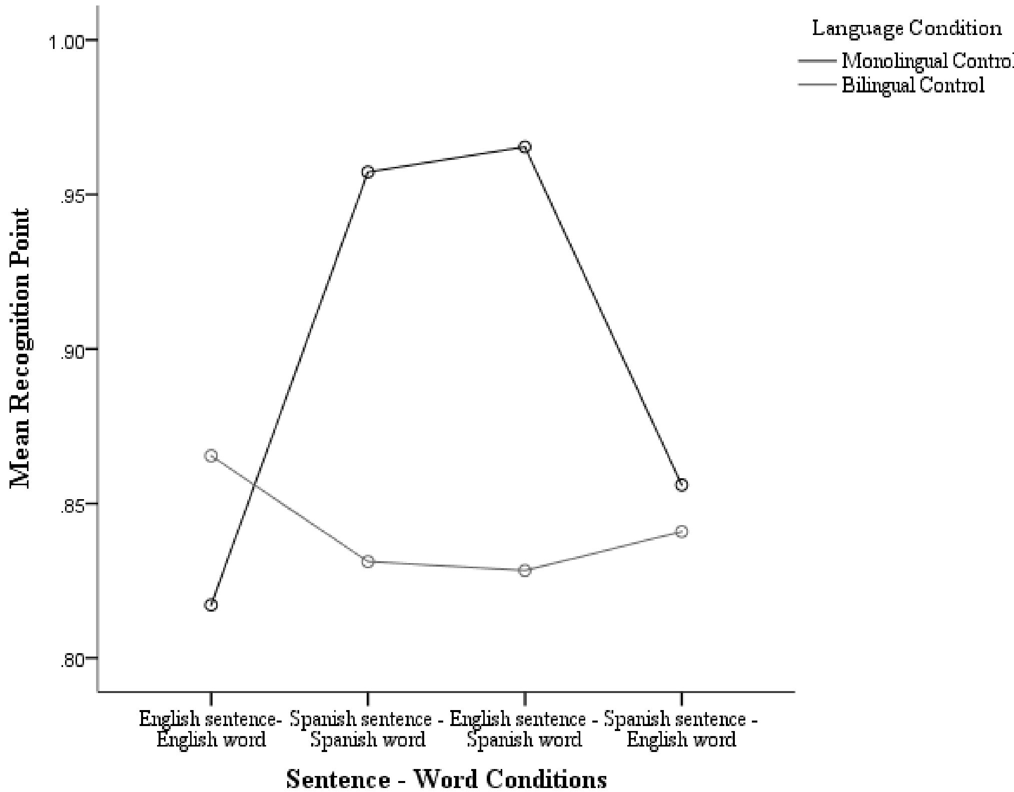

Figure 3. Interaction between language condition and sentence-word condition for recognition point.

Data on the difference between isolation point and recognition point. A 2 (language condition) by 4 (sentence-word condition) mixed-models ANOVA was run with the difference between isolation point and recognition point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. The sentence-word condition referred to the four carrier sentence – target word pairs used: English sentences – English words, English sentences – Spanish words, Spanish sentences – English words, and Spanish sentences – Spanish words.

A significant main effect for sentence-word condition was discovered, $F(3, 32) = 8.28$, $p < .001$, $\eta p^2 = .201$. Spanish-Spanish sentences ($M = .207$, $SE = .018$) had the shortest gap between isolation point and recognition point in comparison to Spanish-English sentences ($M = .215$, $SE = .015$), which in turn had a shorter gap than English-

English sentences (*M* = .249, *SE* = .019), which had a shorter gap than English-Spanish sentences (*M* = .252, *SE* = .020). Recall here that higher numerical values indicate more time elapsing between isolation and recognition point, meaning lower values indicate faster recognition of words.

No significant main effect for language group was discovered, $F(3, 32) = 1.07$, $p = .308$, $\eta p^2 = .031$. Bilingual participants (*M* = .248, *SE* = .029) were similar to monolingual participants (*M* = .213, *SE* = .029) in terms of how much time elapsed between isolation and recognition point.

No significant interaction between sentence-word condition and language group was present, $F(3, 32) = 2.337$, $p = .078$, $\eta p^2 = .066$.

Consonant Voicing Features

Isolation point data. A 2 (language condition) by 2 (consonant voicing features) mixed-models ANOVA was run with isolation point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. Consonant voicing features referred to trials with target words beginning with two initial consonants followed by a vowel (CCV) being classified as either voiced or voiceless.

A significant main effect for consonant voicing features was discovered, $F(1, 34) = 140.03$ $p < .001$, $\eta p^2 = .805$. Participants had earlier isolation points for words beginning with voiceless consonants (*M* = .540, *SE* = .027) than words beginning with voiced consonants (*M* = .674, *SE* = .025).

A significant main effect for language group was also discovered, $F(1, 34) = 6.99$, $p = .012$, $\eta p^2 = .171$. Bilingual participants (*M* = .540, *SE* = .043) experienced isolation point earlier than monolingual participants (*M* = .674, *SE* .027).

A significant interaction between consonant voicing features and language group was present, $F(1, 34) = 14.26$, $p = .001$, $\eta p^2 = .296$. Refer to Figure 4 for a graph of this interaction. An LSD post hoc test revealed that for stimulus words classified as voiced were isolated more quickly by bilingual participants (*M* = .585, *SE* = .761) than monolingual participants (*M* = .761, *SE* = .027), $p = .001$. No differences arose between bilingual participants (*M* = .494, *SE* = .045) and monolingual participants (*M* = .586, *SE* = .028) for words classified as voiceless, $p = .095$. Among monolingual participants, trial words classified as voiceless were isolated more quickly than those classified as voiced, $p < .001$. The same held true for bilingual participants, with voiceless words being isolated more quickly than voiced words, $p < .001$.

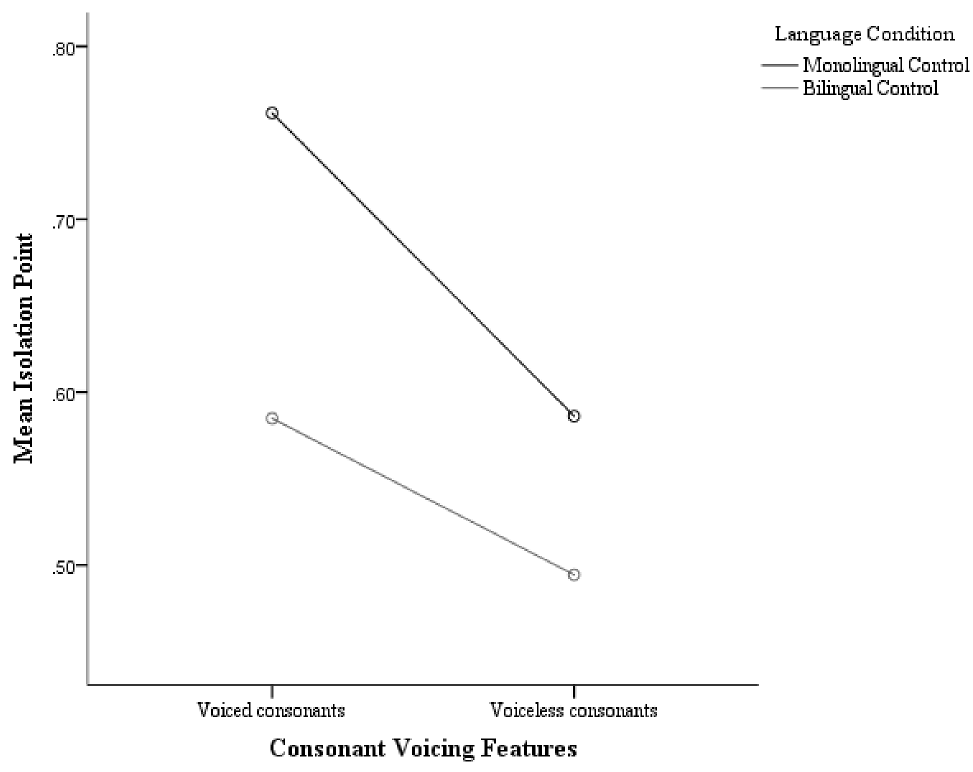

Figure 4. Interaction between language condition and consonant voicing features for isolation point.

Recognition point data. A 2 (language condition) by 2 (consonant voicing features) mixed-models ANOVA was run with recognition point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. Consonant voicing features referred to trials with target words beginning with two initial consonants followed by a vowel (CCV) being classified as either voiced or voiceless.

A significant main effect for consonant voicing features was discovered, $F(1, 34) = 110.13$ $p < .001$, $\eta p^2 = .769$. Words beginning with voiceless consonants ($M = .798$, $SE = .018$) were recognized earlier than words beginning with voiced consonants ($M = .888$, $SE = .016$).

A significant main effect for language group was also discovered, $F(1, 34) = 5.28$, $p = .028$, $\eta p^2 = .138$. Bilingual participants ($M = .806$, $SE = .028$) experienced recognition points earlier than monolingual participants ($M = .880$, SE .016).

A significant interaction between consonant voicing features and language group was present, $F(1, 34) = 9.36$, $p = .004$, $\eta p^2 = .221$. Refer to Figure 5 for a graph of this interaction. An LSD post hoc test revealed that stimulus words classified as voiced were recognized more quickly by bilingual participants ($M = .838$, $SE = .027$) than monolingual participants ($M = .938$, $SE = .016$), $p = .003$. No differences arose between bilingual participants ($M = .774$, $SE = .031$) and monolingual participants ($M = .823$, $SE = .018$) for words classified as voiceless, $p = .186$. However, among monolingual participants, voiceless trials were recognized earlier than voiced trials, $p < .001$. Similarly, bilingual participants recognized voiceless trials earlier than voiced trials, $p < .001$.

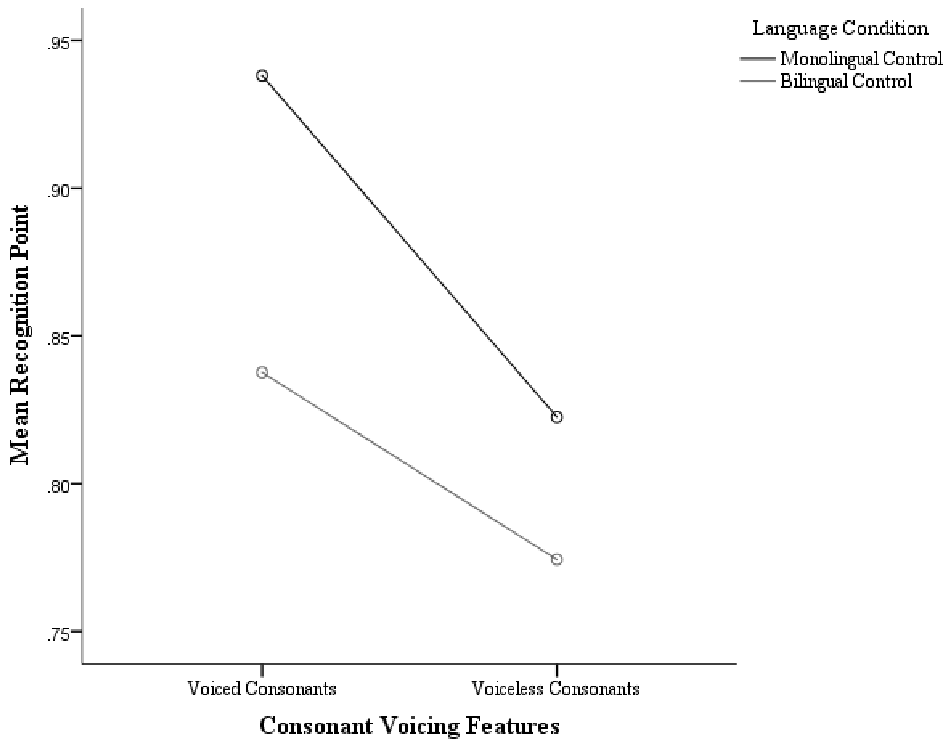

Figure 5. Interaction between language condition and consonant voicing features for recognition point.

Data on the difference between isolation point and recognition point. A 2 (language condition) by 2 (consonant voicing features) mixed-models ANOVA was run with the difference between isolation point and recognition point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. Consonant voicing features referred to trials with target words beginning with two initial consonants followed by a vowel (CCV) being classified as either voiced or voiceless.

A significant main effect for consonant voicing features was discovered, $F(1, 34) = 36.92$, $p < .001$, $\eta p^2 = .528$. Words beginning with voiceless consonants ($M = .246$, $SE = .017$) had a greater gap between isolation point and recognition point than did words beginning with voiced consonants ($M = .199$, $SE = .015$).

No significant main effect for language group was discovered, $F(1, 34) = 1.01$, $p = .320$, $\eta p^2 = .030$. Bilingual participants ($M = .238$, $SE = .027$) were similar to monolingual participants ($M = .207$, SE .016) in terms of how much time elapsed between isolation point and recognition point.

No significant interaction between consonant voicing features and language group was present, $F(1, 34) = 2.58$, $p = .117$, $\eta p^2 = .073$.

Vowel Tenseness

Isolation point data. A 2 (language condition) by 2 (vowel tenseness condition) mixed-models ANOVA was run with isolation point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. Vowel tenseness referred to trials with target words beginning with an initial consonant followed by a vowel (CV) where the vowel was classified as either tense or lax.

No significant main effect for vowel tenseness was discovered, $F(1, 34) = 3.35$ $p = .076$, $\eta p^2 = .090$. Words with tense vowels ($M = .650$, $SE = .028$) had isolation points no different than words with lax vowels ($M = .678$, $SE = .029$).

No significant main effect for language group was discovered, $F(1, 34) = 3.361$, $p = .076$, $\eta p^2 = .090$. Bilingual participants ($M = .614$, $SE = .046$) performed no differently than monolingual participants ($M = .714$, $SE = .029$).

No significant interaction arose between consonant voicing features and language group was present, $F(1, 34) = .140$, $p = .711$, $\eta p^2 = .004$.

Recognition point data. A 2 (language condition) by 2 (vowel tenseness condition) mixed-models ANOVA was run with recognition point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. Vowel tenseness referred to trials with target words beginning with an initial consonant followed by a vowel (CV) where the vowel was classified as either tense or lax.

A significant main effect for vowel tenseness was discovered, $F(1, 34) = 38.42$, $p < .001$, ηp2 = .538. Words with tense vowels (*M* = .888, *SE* = .017) were recognized earlier than words with lax vowels (*M* = .974, *SE* = .016).

No significant main effect for language group was discovered, $F(1, 34) = 1.01$, $p = .323$, $\eta p^2 = .030$. Bilingual participants (*M* = .916, *SE* = .026) performed no differently than monolingual participants (*M* = .946, *SE* = .015).

A significant interaction arose between vowel tenseness and language group was present, $F(1, 34) = 16.43$, $p < .001$, $\eta p^2 = .332$. Refer to Figure 6 for a graph of this interaction. An LSD post hoc test revealed that stimulus words classified as tense were recognized more quickly by bilingual participants (*M* = .845, *SE* = .030) than by monolingual participants (*M* = .931, *SE*= .017), $p = .017$. No differences arose between bilingual (*M* = .961, *SE* = .016) and monolingual (*M* = .986, *SE* = .028) participants for words classified as lax, $p = .443$. Among monolingual participants, tense trial words were recognized more quickly than lax trial words, $p = .042$. The same held true for bilingual participants, with tense words being recognized more quickly than lax words, $p < .001$.

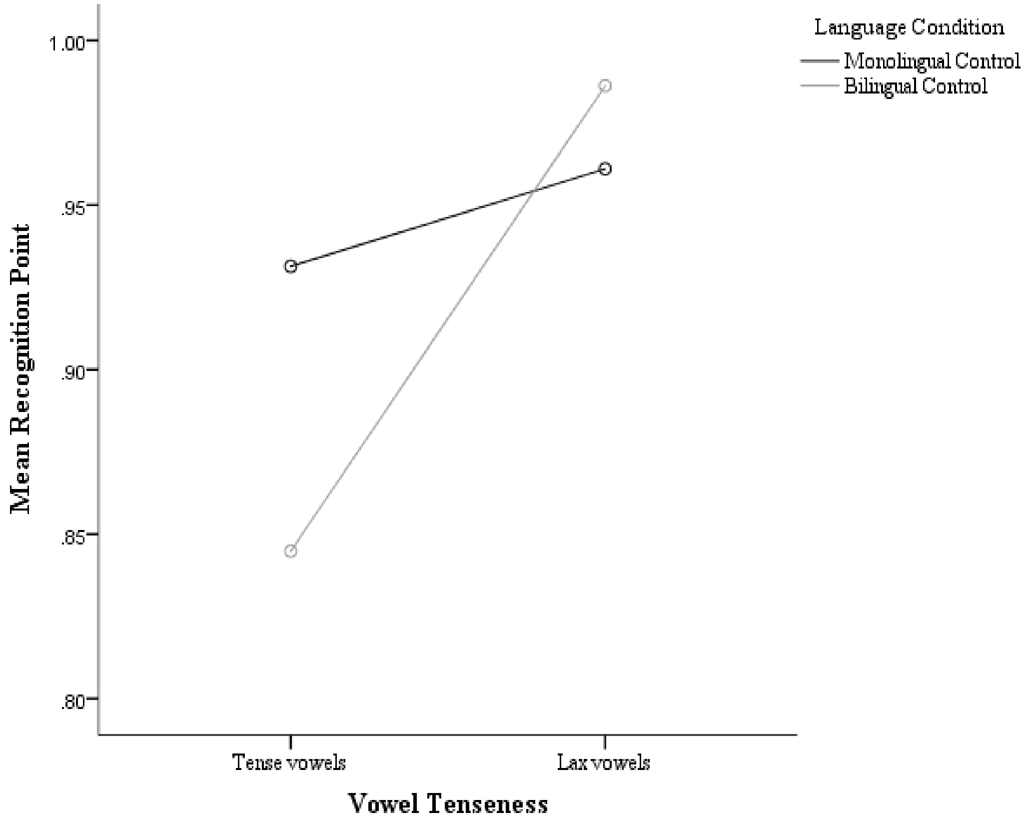

Figure 6. Interaction between language condition and vowel tenseness for recognition point.

Data on the difference between isolation point and recognition point. A 2 (language condition) by 2 (vowel tenseness condition) mixed-models ANOVA was run with the difference between isolation point and recognition point as the dependent variable. The language condition referred to participants' status as either bilingual or monolingual. Vowel tenseness referred to trials with target words beginning with an initial consonant followed by a vowel (CV) where the vowel was classified as either tense or lax.

A significant main effect for vowel tenseness was discovered, $F(1, 34) = 10.50$, $p = .003$, $\eta p^2 = .241$. Results show that for words with tense vowels ($M = .226$, $SE = .020$), less time elapsed between isolation point and recognition point than words with lax vowels ($M = .276$, $SE = .033$).

No significant main effect for language group was discovered, $F(1, 34) = 1.28$, $p = .265$, $\eta p^2 = .038$. Bilingual participants (*M* = .276, *SE* = .033) performed no differently than monolingual participants (*M* = .232, *SE* = .020).

A significant interaction between vowel tenseness and language group was discovered, $F(1, 34) = 7.83$, $p = .008$, $\eta p^2 = .192$. Refer to Figure 7 for a graph of this interaction. An LSD post hoc test revealed that for stimulus words classified as tense, about the same gap between isolation point and recognition point was present in both bilingual (*M* = .224, *SE* = .034) and monolingual participants (*M* = .228, *SE*= .020), $p = .917$. For words classified as lax, bilingual participants (*M* = .327, *SE* = .038) had a larger gap between isolation point and recognition point than monolingual participants (*M* = .236, *SE* = .022), $p = .046$. Among monolingual participants, no differences arose between tense and lax vowel conditions, $p = .666$. For bilingual participants, however, there was a smaller gap between isolation point and recognition point for tense vowel conditions than for lax vowel conditions, $p = .001$.

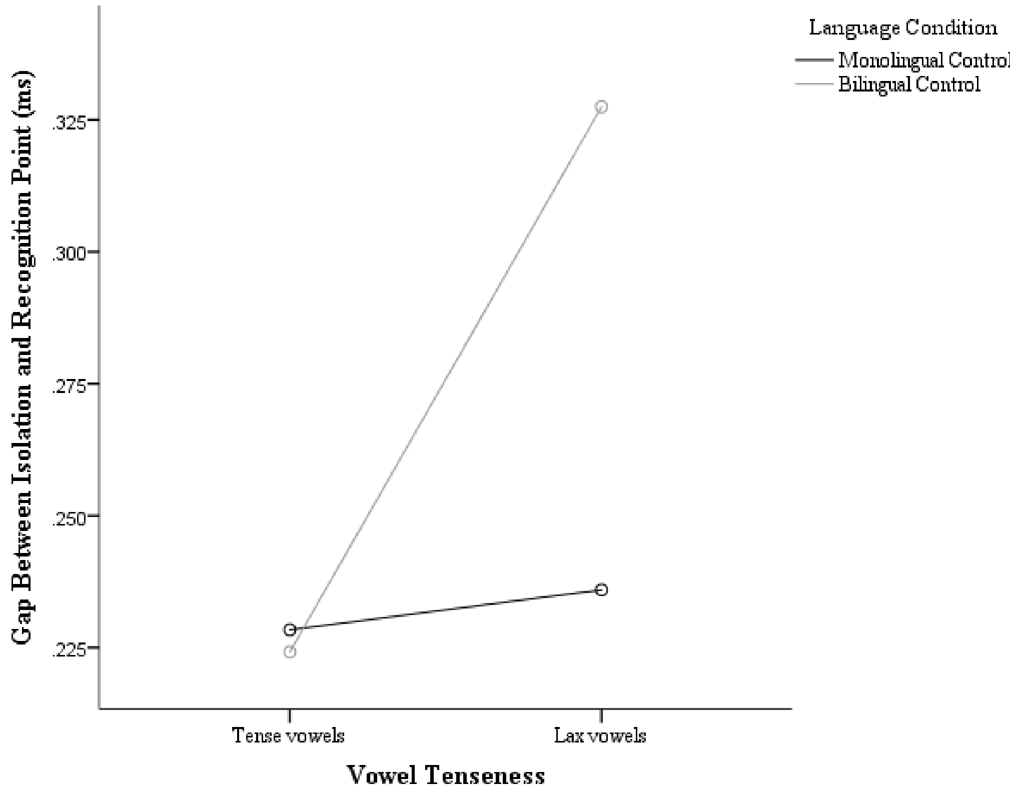

Figure 7. Interaction between language condition and vowel tenseness for the gap between isolation and recognition points.

Neuroimaging Results

Data Analysis

In line with previous studies (Minagawa & Kawai, 2007; Kovelman et al., 2008; Zinszer et al., 2015), changes in blood-oxygenation levels over the course of each trial, from stimulus onset to identification of the word, were examined. Differences between bilingual and monolingual participants were examined for each of the 16 optodes using a series of ANOVAs. Each analysis treated blood oxygenation level as the dependent variable. The first series of analyses treated sentence-word condition (four levels; English sentences - English words, English sentences - Spanish words, Spanish sentences - Spanish words, and Spanish Sentences - English words) and language condition (bilingual, monolingual) as independent variables. The second series of analyses treated consonant voicing features (voiced, voiceless) and language condition (bilingual, monolingual) as the independent variables. The final series of analyses treated vowel voicing features (tense, lax) and language condition (bilingual, monolingual) as the independent variables.

Mean values for neuroimaging data are to be interpreted as follows: scores include both negative and positive values. Positive numbers indicate blood oxygenation rising above baseline levels; negative values indicate blood oxygenation dropping below baseline levels. The greater the number (either positive or negative), the greater the change from baseline.

Sentence-Word Conditions

No significant results were found. For all 16 optodes, blood oxygenation did not significantly vary either across sentence-word conditions or between bilingual and monolingual participants. No significant interactions between sentence-word condition and language group were discovered.

Consonant Voicing Features

A main effect of language group (bilingual, monolingual) was discovered on optode one (located within the dorsolateral prefrontal cortex), $F(1, 34) = 4.646$, $p = .038$, $\eta p^2 = .120$. For words with both voiced and voiceless consonant features, monolingual participants ($M = .009$, $SE = .031$) showed higher blood-oxygenation levels than bilingual participants ($M = -.117$, $SE = .049$).

Vowel Tenseness

Several main effects for vowel condition (lax, tense) were found. These findings are summarized in Table 3, below. It should be noted that in all cases, blood oxygenation levels were higher for trials containing words distinguished by lax vowels. It should also be noted that all such trials were of English words, due to the low prevalence of lax vowels in Spanish.

Table 3. *Blood oxygenation levels for vowel tenseness*

Optode (brain region)	***F*(1, 34)**	***p***	**ηp^2**	**Lax**	**Tense**
1 (left DLPFC)	7.098	.012	.173	*M* = .175, *SE* = .054	*M* = .005, *SE* = .053
3 (left DLPFC)	7.818	.008	.187	*M* = .238, *SE* = .073	*M* = .027, *SE* = .047
4 (left VMPFC)	8.582	.006	.202	*M* = .293, *SE* = .076	*M* = .081, *SE* = .070
5 (left DMPFC)	5.153	.030	.132	*M* = .207, *SE* = .076	*M* = .045, *SE* = .059
13 (right DLPFC)	10.003	.003	.227	*M* = .209, *SE* = .060	*M* = -.009, *SE* = .047
14 (right DLPFC)	4.887	.034	.126	*M* = .175, *SE* = .084	*M* = .010, *SE* = .060
15 (right DLPFC)	9.183	.005	.213	*M* = .201, *SE* = .070	*M* = -.027, *SE* = .048

*DLPFC = dorsolateral prefrontal cortex; DMPFC = dorsomedial prefrontal cortex; VMPFC = ventromedial prefrontal cortex

One significant interaction was observed for optode six, located within the VMPFC, $F(1, 34) = 2.295$, $p = .049$, $\eta p^2 = .109$. An LSD post hoc test was conducted to explore this interaction. On lax vowel trials, bilingual participants (*M* = .393, *SE* = .126) displayed higher levels of blood oxygenation than monolingual participants (*M* = .090, *SE* = .078), *p* = .049. On tense vowel conditions, bilingual participants (*M* = .112, *SE* = .132) did not differ from monolingual participants (*M* = .132, *SE* = .082), *p* = .897. Levels of blood oxygenation in monolingual participants did not differ across lax and tense vowel trials, *p* = .619. However, bilingual participants displayed higher levels of blood oxygenation on lax vowel trials compared to tense vowel trials, *p* = .044.

Chapter 4: Discussion

Analysis of the data revealed a wealth of information, some in line with the original hypotheses and some in contrast to the original hypotheses. To best unpack the large amount of information yielded by the analyses, each hypothesis will be addressed in order.

Hypothesis One

The first hypothesis was that bilinguals would have earlier isolation and recognition points than monolinguals for code-mixed trials due to their proficiency in both languages. This hypothesis was partially supported. Across all sentence-word conditions, bilingual participants had earlier isolation points than monolinguals. The same was true for recognition points, though the results fell slightly above the threshold of significance; it is possible this is attributable to the small sample size resulting in insufficient statistical power.

The most interesting result here, however, is the interaction between language condition and sentence-word condition. Addressing both isolation and recognition point, bilingual participants responded earlier than monolingual participants to Spanish words (English-Spanish sentence conditions and Spanish-Spanish sentence conditions) and at the same speed as monolingual participants for English words (English-English sentence conditions and Spanish-English sentence conditions). These results point to our sample of bilingual individuals being balanced, having vocational proficiency or higher in both English and Spanish. Recall that vocational proficiency is defined as the ability to communicate fluently in all situations pertinent to social and community life, and in almost all situations specific to one's vocational field (Wylie & Ingram, 2010). The sample included both bilinguals with an L1 of English and bilinguals with an L1 of Spanish, with bilingual participants with an L1 of English (seven of ten participants) outnumbering those with and L1 of Spanish (three of ten participants). This could be the reason that recognition of English words was similar between monolinguals and bilinguals. However, it should also be noted that most bilingual participants had an early onset of L2. Prior research indicates early onset of L2 is important for attaining native-like levels of proficiency (Snow & Hoefnagel-Hohle, 1978), especially regarding phonetics (Norrman & Bylund, 2016), at no detriment to L1 abilities. Also interesting is the finding that bilingual participants did not differ significantly in terms of isolation point or recognition point for any of the sentence-language conditions. This, too, points to bilingual participants having balanced proficiency in each known language.

Monolingual participants performed quite differently. Consistent with the hypothesis, which implied that English words would be easier to recognize, and that code-mixed conditions would pose more of a challenge than single-language conditions, monolingual participants both isolated and recognized English sentence – English word trials most quickly; this was followed by Spanish sentences – English words, English sentences – Spanish words, and finally Spanish sentences – Spanish words. Of most interest here are the carrier sentence – target word findings. Language of the carrier sentence seems to aid monolingual participants in some instances and hinder them in others. For example, when the carrier sentence was in a foreign language but the target word was in the participant's native language, isolation and recognition were slower than when both sentence and target word were in the participant's native language. This is to be expected. However, something caused English carrier sentences with Spanish words to be isolated more quickly than Spanish carrier sentences with Spanish words, but to be recognized more slowly than Spanish carrier sentences with Spanish words. Recognition of English carrier sentences – Spanish words could have been slower than recognition of Spanish carrier sentences – Spanish words because the code-mixing created confusion. Recall that two correct identifications with 100% confidence are required for recognition point to occur; as more gates of a word were revealed, monolingual participants might have turned to second-guessing themselves. For isolation point, on the other hand, there are a few possible explanations for why English carrier sentences with Spanish target words were more quickly recognized than all-Spanish sentence-word pairs. All sentences made grammatical sense (e.g., sentences beginning with "I want the…" always ended with a noun and never with a verb). It is possible that this provided some sort of context for monolingual participants to utilize, causing the earlier isolation points. Janse and Ernestus (2011), Ryalls (1996), and Marslen-Wilson (1987) emphasize the importance of context for aiding word recognition. Future research should explore if this effect emerges with sentence-word pairs that are non-grammatical, erasing any benefits of context. Additionally, even though participants who were monolingual did not speak Spanish, it is quite possible that due to the region (Florida), these participants had some sort of familiarity with Spanish, either encountering it in grade school, in the homes of friends, in the workplace, etc. It is not clear exactly how much familiarity with Spanish monolingual participants had, nor is it clear what degree of familiarity with a foreign language is necessary to make word-identification easier in a code-mixing context. Keep in mind that no monolingual participants in the current study met Spanish proficiency levels as defined by the ISLPR (Wylie & Ingram, 1999). It is possible that limited familiarity may hinder, not aid, word identification. For example, observation of participants during the experiment suggested that some monolinguals had difficulty identifying the correct Spanish word (e.g., saying "problemo" instead of "problema"). This could be tied to an issue of vocabulary limitations, such as the correct Spanish term simply existing outside of the monolingual speakers' lexicon of known words, causing perseveration and resulting in monolinguals' inability to process these words as efficiently or quickly as bilinguals. Future research should explore if a similar effect emerges when using the design of the current study with monolingual participants who have had very little or no exposure to the foreign language being used.

Hypothesis Two

It was hypothesized that bilinguals would display higher blood-oxygenation levels than monolinguals for code-mixed (Spanish-English and English-Spanish) trials. This was not supported by the data; by contrast, no differences in oxygenation levels arose between bilinguals and monolinguals for any sentence-word conditions. Additionally, no differences in blood-oxygenation appeared among any of the sentence-language conditions. This is contrary to prior fNIRS research (Kovelman et al., 2008) indicating changes in DLPFC oxygenation as participants recognize words in different languages. This could be because Kovelman et al.'s (2008) research used a semantic judgement task, which involved mapping pictures to words, not with hearing and identifying spoken words. Kovelman et al. (2008) also presented each language in isolation (not code-mixed in sentences). It is likely that differences in processing on the type of task used in the present study, both between monolinguals and bilinguals and among different sentence-word conditions, are localized in a different area of the brain. The fNIRS band employed in the present study reaches near to, but does not completely overlap, Broca's area, nor does it cover the primary auditory cortex. Future research should employ fNIRS devices or other neuroimaging technologies that cover a larger area of the scalp to better detect any changes in processing that might be occurring.

Hypothesis Three

The third hypothesis stated that monolinguals should show later isolation points and recognition points than bilinguals for voiced consonant trials, given that unlike Spanish, words in English do not have negative VOTs (vocalization occurring before plosive release) (Piccinini & Arvaniti, 2015). The data revealed information contrary to the original predictions. Though bilingual participants had earlier isolation and recognition points than monolingual participants for both voiced and voiceless conditions (pointing to bilinguals being able to distinguish between prevoicing and post-voicing), all participants, regardless of language group, were faster to isolate and recognize voiceless words than voiced words.

Post-hoc analyses revealed that bilinguals were faster than monolinguals when isolating and recognizing voiced (but not voiceless) words. This could indicate that bilinguals are more sensitive to differences between short and long lags. Because Spanish has words with both a negative VOT (prevoicing) and positive VOT (short lag voiced words) (Balukas & Koops, 2015), it is possible that Spanish-speaking bilinguals are more sensitive to these types of voicing features than English-speaking monolinguals. It is also possible that the longer lags of English voiced words, not present in Spanish words (Brice, personal correspondence, February 6th, 2017), make English words with long lags more easily distinguished by bilinguals. Recall the cohort effect as described by Marslen-

Wilson (1987), where multiple word candidates form a cohort of possible words based upon both bottom-up acoustic-phonetic input and top-down contextual or semantic information. The ability of bilinguals to better discriminate between short and long lags for voiced words could be due to these language-specific differences in voicing features helping bilinguals to start ruling out word candidates, shrinking the size of the cohort and aiding in faster recognition. Monolinguals, on the other hand, not as sensitive to these differences in voicing features, would remain sifting through a larger cohort of possible words and neither isolate nor recognize the word until later than bilinguals.

However, this does not explain why voiceless words were recognized more quickly than voiced words for both monolinguals and bilinguals, especially given that a sample with a larger monolingual subject pool than bilingual subject pool would be expected, if anything, to throw results in the opposite direction (toward voiced words being recognized more quickly). A number of reasons could explain these findings. Here we must consider the fact that while voiceless words were isolated and recognized more quickly than voiced words, there was a greater gap between isolation point and recognition point for voiceless words in comparison to voiced words. Keeping in mind that stimulus words were presented in a neutral context, it might be that the earlier VOT of voiceless words, in which early gates often end somewhat abruptly, makes these voiceless words more perceptible and results in an earlier isolation point (F. Grosjean, personal correspondence, February 8, 2017). Following this, participants' lack of need to distinguish between short and long lags results in an earlier recognition point as well. If monolinguals did indeed experience difficulty discriminating between short and long lags in words with voiced consonants, it is possible that this caused isolation and recognition of such words to be delayed in comparison to the earlier VOT voiceless words. It is also possible that voiceless words in this study had a higher frequency of occurrence or were more familiar to participants than voiced words; each of these qualities having the possibility of contributing to the earlier isolation and recognition points observed.

Hypothesis Four

It was hypothesized that blood oxygenation would be higher in monolingual participants for voiced conditions, given the low prevalence of negative VOT words in English but not in Spanish (Balukas & Koops, 2015; Brice & Brice, 2008; Piccinini & Arvanitit, 2015). This hypothesis was only partially supported. Contrary to what was expected, monolingual participants showed greater blood oxygenation levels than bilinguals on both voiced and voiceless trials for optode one, located in the left DLPFC. This suggests that bilingual individuals showed increased neural efficiency in this area, as other bilingualism research (Gold, Kim, Johnson, Kryscio, & Smith, 2013) has tied lower blood oxygenation levels with greater neural efficiency. It is possible that differences only appeared on optode one because this optode is closest to Broca's area.

Hypothesis Five

It was hypothesized that bilingual participants would display later isolation and recognition points in relation to monolingual participants on lax vowel trials, due to the absence of lax vowels in Spanish (Brice & Brice, 2008). This hypothesis was not supported. For isolation point, no effect of language group, vowel tenseness, or interaction between the two was present. For recognition point, while tense vowels were recognized more quickly than lax vowels, no differences emerged between bilinguals and monolinguals across vowel conditions. In terms of the interaction between language group and vowel tenseness, bilingual participants recognized tense vowels more quickly than monolinguals, but performance did not differ between monolingual and bilingual participants for lax vowels. Among both monolingual and bilingual participants, tense vowels were recognized more quickly than lax vowels. This can be partially explained by the paucity of lax vowels in Spanish (Brice & Brice, 2008) driving tense-vowel words to be recognized more quickly. However, this does not fully explain why both bilingual and monolingual participants recognized tense vowels more quickly than lax vowels. A search of the literature on American English phonetic features and word frequency yielded no definitive answer on the prevalence of words containing tense vowels in comparison to words containing lax vowels. Thus, it is possible, but unknown, if words with tense vowels simply have a higher frequency than words with lax vowels and are thus more easily recognized. Future research should attempt to identify and match the frequency and neighborhood density of stimulus words, in order to eliminate the possibility that word frequency and not vowel tenseness produced the effects discovered in this research.

Hypothesis Six

It was hypothesized that, again due to the absence of lax vowels in Spanish (Brice & Brice, 2008), bilinguals would have higher blood-oxygenation levels than monolinguals on lax vowel words. This hypothesis was partially supported. Of interest, several main effects were observed for vowel tenseness, where regardless of language condition (bilingual, monolingual), blood oxygenation levels were higher for lax vowels than for tense vowels. This was the case for several optodes spanning the left DLPFC, ventro- and dorso- medial PFC, and right DLPFC. This suggests that there is some quality to the words classified as having lax vowels which is causing participants to expend more energy identifying these words. While it could be that tense vowels are more distinctive than lax vowels, at least in English, there is not yet any research to support this hypothesis.

Also interesting was the interaction between language condition and vowel tenseness on optode six, located in the VMPFC. Here, bilingual participants displayed higher levels of blood oxygenation than monolinguals for lax vowels, although no difference between these groups was observed for tense vowels. Some differences in oxygenation were expected given the prior findings of Kovelman et al. (2008), who observed greater DLPFC activation in bilinguals as compared to monolinguals during a semantic judgement task (e.g., does the meaning of the word match the picture presented?) using words presented both visually and aurally. Jasinska and Petitto (2013) also observed more PFC oxygenation in late-onset bilinguals when judging visually-presented sentences as grammatically plausible or implausible.

What is not clear is why this difference appeared only in one area of the VMPFC, and why differences were present only for lax vowels. There are a number of potential explanations for this, including the idea that lax vowels being scarce in Spanish caused more decision-making effort to be expended on such trials in the bilingual group. Additionally, it is unclear if the VMPFC was indeed the only area where differences occurred, or if limitations of small sample size in the bilingual group obscured trends on other optodes that would have become apparent with a larger number of participants. The fact that other researchers (Kovelman et al., 2008; Jasinska & Petitto, 2013) discovered differences in oxygenation levels elsewhere in the prefrontal cortex suggests that the power, and not a mere lack of effect, may have been an issue in the present study.

Limitations, Strengths, and Future Directions

As with any research design, the present study was not without limitations. Foremost among these was the small number of participants and unequal group sizes. While it is common in language research for studies to have small sample sizes, future research should strive to collect data from enough participants to ensure adequate statistical power for a given research and data analysis design. Furthermore, future research should strive to obtain as homogenous a sample of bilingual participants as possible. In the present study, bilingual participants were mixed in terms of Spanish being either L1 or L2. Additionally, most but not all of the bilingual participants in the sample were classified as having an early onset of L2. While this was considered an acceptable limitation of the study given the already small pool of bilingual participants, future research should endeavor to make the sample of bilingual individuals as homogenous as possible. This will help to erase the possibility that, despite spoken proficiency, differences in onset of L2 could have influenced how participants were perceiving phonetic features of words.

Since there are so many factors influencing word identification, such as frequency, word length, and neighborhood density (F. Grosjean, personal correspondence, Feb 8, 2017), future research should try to control for as many of these variables as possible. The present study restricted the word list to nouns, all presented in a neutral context, which allowed for an examination of features other than context affecting word recognition. In addition to this, future research could examine words of similar length (e.g., either disyllabic or trisyllabic words) and of similar frequency of occurrence (e.g., common words). The present study also examined only bilinguals who were proficient in Spanish and English for the sake of keeping the study design reasonably simple. Future researchers should consider including those who are multilingual, comparing them both to bilingual and monolingual individuals. This could be particularly advantageous in study designs where L1 and L2 are not very closely related (e.g., Cantonese and Spanish as opposed to Spanish and English); it is possible that if multilingual individuals know a wider breadth of languages, word recognition might be improved in this group.

As mentioned earlier, the present study included monolinguals who may have had some length of exposure to Spanish, either in the workplace, among friends, or from a few years of grade-school language classes. While this exposure was not great enough to push any of our monolingual participants into being classified as having any significant amount of spoken proficiency with Spanish, future research should take into account monolingual participants' familiarity with any non-native languages being used in the research. This is especially relevant given the popularity of Spanish as a spoken language and rising levels of bilingualism throughout the world; more and more people will experience some length of exposure to one or more non-native languages. It is not yet clear if some familiarity, but not any proficiency, with other languages is a beneficial or hindering factor in scenarios of word recognition involving multiple languages.

General Conclusions

Our findings support the idea that bilinguals are capable of native-like proficiency, with patterns of prefrontal cortex oxygenation very similar to monolinguals in terms of recognizing English words. Differences arise when examining voicing features unique to one language (i.e., lax vowels only occurring in English, not Spanish). Our findings also support the idea that while holding native-like proficiency, bilinguals are also more sensitive than monolinguals to voicing features that distinguish one language from another.

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Appendix

Bilingual Screening Questionnaire

Screening Questionnaire

If you have any discomfort with any questions please feel free to leave the question blank

1. Are you monolingual or bilingual? ____
2. What languages do you speak? ____
3. How many languages do you know? ____
4. What do you consider to be your first language or primary language? ___________________
5. What do you consider to be your secondary language? _______________________________
6. How long have you spoken your primary language? _________________________________
7. If bilingual, how long have you spoken your secondary language? ______________________
8. Rate your proficiency in the languages that you know where "1" is the lowest and "5" is the highest.

• English.	1	2	3	4	5	
• Spanish	1	2	3	4	5	
• Other language	1	2	3	4	5	which language _______
•	1	2	3	4	5	which language _______
•	1	2	3	4	5	which language _______

9. Have you ever studied any other languages? If so for how long? ________________________
____
10. In the past have you experienced any brain injury (ies)? Yes No
11. If so please describe.
____
____
____
____
12. Are you currently taking any medication that could cause drowsiness? Yes No
13. Have you ever been diagnosed with a language disorders? Yes No
14. If so please describe.
____