5-13-2019

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B.A., University of Connecticut, 2017


A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Arts at the

University of Connecticut

2019

APPROVAL PAGE

Master of Arts Thesis

# Bilinguals' Double Phonemic Boundary: Not One of Normal Nature

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University of Connecticut

2019

## Acknowledgements

The author acknowledges the support and encouragement of her advisor, Adrian Garcia-Sierra, Ph.D. whom inspired and challenged her throughout these past couple of years to think critically and never stop asking questions. The author would also like to thank her friends and family for their patience and support throughout this process.

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**Abstract**

The present investigation reports the conditions that propel bilinguals' double phonemic boundary, a phenomenon where bilinguals' perception of speech sounds is affected by the linguistic context in which they are immersed, and theories that support bilinguals' phonetic category structures while taking into consideration different auditory biases that could influence the double phonemic boundary such as contrast-effects, range-effects, and resource allocation. Thirty-three right-handed participants performed a Go/No-Go-Task. The sample consisted of 16 English monolinguals and 17 Spanish-English bilinguals. Participants were instructed to press a response button, using the right or left hand, when detecting 3 target sounds embedded in 6 background sounds. Two conditions were collected. In the Spanish phonetic context, 3 short-lag target sound consonants were embedded in 6 Spanish-like /ba/ sounds. While in the English phonetic context, the same target sounds were embedded in 6 English-like /pa/ sounds. Each background sound followed a target sound equally often, but stimulus presentation was kept otherwise random. It was explored if the perception of target sounds changed between phonetic contexts. Results demonstrated a double phonemic boundary for bilinguals, but not for monolinguals, with a right-hand advantage for bilinguals in both conditions. The degree of shift noted in bilinguals' perceptual shift was correlated with language confidence. Bilinguals' double phonemic boundary may be the result of resource allocation, as bilinguals were able to perform better on the perceptual task than monolinguals. Unexpectedly, monolinguals only showed right-hand advantages in the Spanish phonetic context, and left-hand responders pressed the button significantly fewer times than their right-hand responder counterparts. Executive function differences between bilinguals and monolinguals are addressed.

## Introduction

Bilinguals are faced with the unique cognitive challenge of accurately distinguishing and interpreting two languages at any given moment. There exists significant evidence that linguistic context guides bilinguals' speech perception when confronted with overlapping speech characteristics of two or more languages. This context, mostly the acoustics of speech sounds and linguistic information, biases the bilingual listener. Therefore, by altering the context heard by bilinguals, the perception of speech characteristics of the same acoustic measurements can be disambiguated (Grosjean, 1985a). Our analysis expands upon this premise by exploring bilinguals' capacity to discriminate between speech sounds with similar acoustic characteristics in English and Spanish that hold different phonemic-meaning depending on the language being heard or spoken. In accordance with Garcia-Sierra, Diehl, and Champlin (2009), this is what is known as the double phonemic representation; bilinguals' ability to develop two phonemic representations for a single acoustic-phonetic event (Elman, Diehl, & Buchwald, 1977; García-Sierra, Diehl, & Champlin, 2009).

This paper will explore the intricacies behind the contexts that shape the processing of specific speech sounds. More precisely, language contexts, phonetic contexts, and other effects of normal nature that provide insight into bilinguals' and monolinguals' speech perception will be discussed. Previous research also suggests that bilinguals gain enhanced attentional control associated with having two language representations, tested via assessments of executive functions (Bialystok, 2011; Bialystok, Craik, & Luk, 2012). The present investigation examines the influence that phonetic contexts have on speech perception in bilinguals and the role that enhanced attentional resources may play in bilinguals' ability to attenuate to a perceptual task. To test these features, a bilabial VOT continuum of English and Spanish stop consonants comprises the stimuli used in the present investigation. First, the distinctions between Spanish and English stop consonant productions are outlined along with the appropriate theoretical models.

To distinguish between two speech sounds, we must first group the acoustic information into phonetic categories. This is done by discriminating between speech sounds in order to place the speech sound perceptually. For example, most languages have a voicing contrast for initial stop consonants (1) voicing lead or prevoicing (negative VOT); (2) coincident and short-lag VOT (zero or short positive VOT duration); and (3) long-lag VOT (large durations of positive VOT) (Abramson & Lisker, 1967, 1972; Lisker & Abramson, 1964). These perceptual cues allow individuals to place the appropriate sound into their phonetic category. In many romance languages as Spanish, voiced stop consonants /b/, /d/, and /g/ are produced with negative voice onset time (VOT); voicing occurs before the onset of the consonant. Voicing lead occurs much less frequently in the production of English voiced stop consonants, but it has been reported to occur (Keating, Mikos, & Ganong, 1981; Hay 2005; Antoniou, Best, Tyler, & Kroos, 2010; Fish, García-Sierra, Ramírez-Esparza, & Kuhl, 2017). In many Germanic languages, including English, voiced stops /b/, /d/, and /g/ are produced with short durations of positive VOT; voicing occurs at or after the onset of the stop consonant. Similar to English, the voiced stop consonants of Spanish /p/, /t/, and /k/ are also produced with short durations of positive VOT, making them phonetically similar to the English /b/, /d/, and /g/. On the other hand, English voiceless stop consonants /p/, /t/, and /k/ fall in the long-lag VOT voicing contrast, (with large positive VOT values), which does not occur in the Spanish language (Caramazza, Yeni-Komshian, Zurif, & Carbone, 1973; Williams, 1977).

This investigation will focus on short-lag stop consonants, since these phonemes exist in different phonemic categories depending on the language, Spanish or English. Spanish monolinguals perceive short-lag stops as /p/, /t/, and /k/, while English monolinguals perceive these same short-lag stops as /b/, /d/, and /g/. We will be focusing on this phonetic overlap to determine how bilinguals organize their phonetic categories. Further, the way in which bilinguals structure their phonetic categories impacts how they perceive and produce these stop consonants.

Models of speech perception are discussed to explain how it is that a monolingual and a bilingual may interpret this phonetic overlap. One model in particular, The Perceptual Assimilation Model (PAM; Best 1994, 1995) addresses how nonnative phones are perceived by monolinguals. Usually, a monolingual will assimilate nonnative speech sounds to pre-existing categories of their native language in a way that either categorizes the sound correctly or incorrectly. The following terms reviewed outline what may occur during monolinguals' perception of nonnative phones.

When a monolingual is presented with two nonnative phones and these phones are perceived as belonging to two different native categories, two-category assimilation has occurred, meaning discrimination is excellent. Uncategorized-categorized pair appears when one nonnative phone is not considered as belonging to a native category but the other is assimilated to a native speech sound category. Discrimination is poor when single category assimilation occurs; two nonnative speech sounds are perceived as equal phones of the same phonetic category. Lastly, category goodness assimilation results when two nonnative speech sounds are placed in the same category, but one phone is perceived as a better exemplar (Best 1994, 1995). PAM describes monolinguals' perceptual categorization, but when it comes to bilinguals, adjustment of this perceptual model is necessary since only one phonetic system is utilized for monolinguals.

PAM-L2 (Best & Tyler, 2007) is a theoretical model that explains bilingual's perceptual categorization patterns. First, to account for new L2 learners, Best and Tyler (2007) theorized that in order to accommodate for both languages, two distinct regions of phonetic space for each of their languages must exist within a common L1/L2 phonological category. For example, bilinguals can perceive phonetic differences between Spanish and English productions of /p/, but they can also recognize that these productions have a shared phonological contrast (e.g., /b/ vs. /p/). This perspective focuses on L2 learners that are in the process of actively acquiring their second language. Level of bilingualism is impacted by characteristics such as age of onset, amount and quality of input from native L2 speakers, how long the individual has been in an L2 speaking environment, and their ratio of usage between their L1 and L2. PAM-L2 makes the assumption that L2-dominant bilinguals (early sequential bilinguals) will have distinguished L2 categories, separate phonetic categories from those of their L1. Late L2 learners are postulated to perceive articulatory gestures of a speaker to decipher phonetic contrasts, instead of benefitting from two distinct phonetic representations from each of their languages. Other models also describe the theoretical processes behind the processing of speech sounds.

The Speech Learning Model (SLM) is a theory regarding the restructuring of the phonemic representation (Flege, 1995). The phonetic systems are believed to reorganize when speech sounds perceived in the L2 can be discriminated due to the addition of new phonetic categories or the adjustment of old ones. When the L2 phonetic categories merge with the preexisting L1 phonetic categories, Flege (1995) refers to this as assimilation. This theory suggests that second language learning and the development of a complete phonetic system is not reliant on access to second language learning during the critical period, but that mechanisms used to learn the L1 may be available throughout the lifespan. SLM posits that L1 phonetic categories are consistently adjusted and L2 phones may be identified within those categories, and moreover, L1 influences on L2 may exist, otherwise called cross language interference. Phonemes across languages may be distinct and have the potential to be produced correctly. Even so, these theories do not take into consideration the effects of language contexts on bilinguals' ability to categorize speech sounds in a monolingual-like way.

The specific theoretical organization of language still remains a topic of discussion, and the main debate questions the existence of two possible phonetic structures for bilinguals. One possibility is that bilinguals have separate phonetic categories for second language phones. The latter is that bilinguals have a single set of merged phonetic categories. The present experiment aims to achieve evidence for the existence of two separate phonetic representations (i.e., the double phonemic representation) by studying whether or not bilinguals' perception of phonetic contrasts is altered by their context. Phonetic category structure is often assessed to determine if the double phonemic representation exists and it is accomplished by placing bilinguals in a language mode, constructed via a language context.

"Language mode" refers to the idea that bilinguals' speech perception and production may not be fixed but rather sensitive to the language input and output they are experiencing. A "mode" in this context is a state of activation of a bilingual's language processing systems as well as their first and second languages (Grosjean, 1998). Grosjean (1998, 2001, 2008) proposed The Language Mode Framework which postulates that a bilingual's languages may be activated or deactivated depending on the language being used at a given moment. In "monolingual mode," one language is activated, and the other language is diffused, although never completely deactivated. Contrarily, "bilingual mode" assumes that both languages are activated.

To further expand, bilinguals are described as moving along a "monolingual-bilingual" continuum (Grosjean, 1998). Along this continuum are various activations of each language, ruled by variables such as who the bilingual is listening to, speaking with, or even the topic or purpose of the interaction. For example, bilinguals may be in monolingual mode when conversing with a monolingual speaker of one of their languages, where their other language is deactivated. On the bilingual end of the continuum, bilinguals can be in a bilingual mode when communicating with a bilingual speaker of the same languages, where language mixing may take place. Here, both languages would be activated. Most importantly, language modes are presumed to affect all aspects of language processing (e.g., morphological, lexical, syntactic, etc.) (Grosjean, 1998). Studies of language mode effects on production offer us insight on the double phonemic representation. If a bilingual can shape their productions of both languages to be comparable to monolinguals of both of their languages, this may be indicative of two separate phonetic systems. Furthermore, perhaps this logic holds true for perception as well.

**Studies of language mode effects on speech production**

Antoniou, Best, Tyler, and Kroos (2010) interpreted Grosjean's (2001) language mode framework and applied it to their study of bilinguals' speech production. They posited that bilinguals' speech output should function along the monolingual-bilingual continuum where a bilingual functioning in monolingual mode should be perceived as monolingual-like. When bilinguals are producing speech in a monolingual-like way, this has been interpreted as indication that they have separate language-specific categories. If bilinguals produce in-between values, a more accented production, then increased interaction between the L1 and L2 would be assumed, demonstrating phonetic merger (Antoniou, Best, Tyler & Kroos, 2010). One way to test this theory is by measuring VOT of stop consonant productions. Early sequential bilinguals were used in these studies since onset of L2 learning is correlated with increased goodness ratings for productions of stop consonants in children (Flege et al., 1996).

Antoniou and colleagues (2010) tested the effect of language mode on bilinguals' speech production by assessing Greek and English monolinguals and L2 dominant early sequential Greek-English bilinguals' stop consonant productions (/b/, /p/, /d/, and /t/) in English and Greek language modes. In Greek, much like Spanish, voiceless stop consonants /p/ and /t/ have short-lag, unaspirated VOT. This is similar to English voiced stops /b/ and /d/, which also have short-lag, unaspirated VOT in the word-initial position. The researchers predicted that the bilinguals would produce different language-specific VOTs depending on the language mode in which they were placed. Bilingual and monolingual participants produced /p/, /t/, /b/, and /d/ in the word-initial position of CV word shapes /pa/, /ta/, /ba/, and /da/ and in medial postvocalic contexts and in VCV word shapes. Monolingual productions were taken for comparison. In English mode, bilinguals produced slightly prevoiced /b/ and produced English /d/ with short-lag VOT. Voiceless stops /p/ and /t/ were produced with long-lag VOT. Bilinguals in Greek mode produced stop consonants like Greek monolinguals; Greek /b/, /d/ had substantial voicing lead, and /p/, /t/ had short-lag VOT. When the bilinguals were put in a language mode, they produced native-like stop voicing VOT values almost identical to the monolingual speakers, with the exception of some variation in medial contexts for bilinguals in Greek mode.

The results of Antoniou et al. (2010) show that language mode has considerable effects on bilinguals' speech production as productions varied depending upon language context. Findings suggest that bilinguals show diminished L1-L2 interferences and evidence of language-specific phonetic categories. A similar study was later performed that forced bilinguals to code switch (L1 language targets were embedded in L2 carrier phrases) where bilinguals' productions were altered, revealing that bilinguals are unable to suppress the L1 effect on their L2, further indicating that language mode is important for bilinguals to verbalize correct productions. Otherwise, accentedness can be intensified between their languages as well, creating language-relevant VOT shifts (Antoniou et al., 2010; Sancier & Fowler, 1997).

Sancier and Fowler (1997) provided a case study of a Portuguese-English bilingual who spent a portion of the year in Brazil speaking Portuguese and another portion of the year speaking in English in the United States. Productions were recorded after each stay; native English and native Portuguese speakers rated the productions as sounding more or less foreign-accented. A gestural shift was appreciated across the L1 and L2 evidenced by the listeners' perceptual judgements of the bilingual's productions, stop consonants especially. Therefore, not only can language mode effect a bilingual's productions via acoustic analysis, but this shift in production can also be recognized perceptually by unfamiliar listeners.

Fowler and colleagues (2008) tested French-English simultaneous bilinguals' productions after exposure to a language mode. Language contexts were found to be significant, as bilinguals' productions adjusted based on the context. Bilinguals' productions were similar to monolingual productions, only they were more exaggerated, suggesting that the cross language phonetic cue of short-lag versus long-lag VOT was emphasized. These results have been interpreted that cross-language phonetic categories exist in the speech of bilingual speakers. Bergman and colleagues (2016) similarly found that L1 speech sounds come to resemble those of similar L2 speech sounds, evidence for L2-induced change. Overspecification of monolingual participants' speech sound productions suggests this may not be a phenomenon seen in bilinguals

(Schertz, 2016). Additionally, this effect has been seen with new L2 learners of Asian languages.

Chang (2012) studied the effects of L2 learning on speech production. Adult native English speakers completed elementary Korean classes and their speech production was subsequently analyzed. Learners' English productions were found to be influenced by their brief experience with Korean in voiceless stop and vowel productions, most namely. Since participants' exposure to L2 influenced their L1, this was understood as evidence for cross-language phonetic drift. Subtle phonological restructuring in the L1, as a consequence of L2 experience, is a phenomenon referred to as phonetic drift. It seems that our phonetic systems may be more dynamic than originally thought; however, amount of exposure to language does matter. Chang (2013) posited that the reason for this shift in production is due to a novelty effect, since they found a more pronounced phonetic drift in inexperienced L2 learners as compared to experienced L2 learners. L2 learners do not appear to have the same adjustments in their phonetic categorization as do bilinguals (Chang, 2013, & Hao, 2016). There is no doubt that there is a link between perception and production; however, perceptual studies allow us to assess the phonological implications in isolation.

**Studies of language mode effects on speech perception**

Bilinguals' double phonemic representation is normally assessed by asking participants to identify stop consonants in two language contexts. For example, when Spanish-English bilinguals are tested, it is assumed that the phonetic boundary dividing the voicing lead category from the short-lag category will shift toward the voicing lead category during the Spanish language context, and that it will shift toward the short-lag category during the English language context. However, the methodological differences in studies assessing the mechanism of double phonemic representation have been vast. Most notably, there are variances in the way contexts are established and in the inclusion or absence of monolinguals as control groups.

Antoniou and colleagues (2012) employed a similar investigation to their previous studies, however, with the focus now on perception instead of production. They compared monolinguals' perception of stop consonants to that of bilinguals. The main goal was to also test if bilinguals have merged or separate phonetic categories. Stimuli used were CV syllable shapes /pa, /ta/, /ba/, and /da/ of Greek and English. Four recordings of each stop were used for each language, with varying VOTs. Language mode was established via conversation with experimenter in language of interest. The two categorization tasks included a goodness rating and a categorical AXB discrimination task of Greek and English versions of same contrasts (i.e. /b/ and /p/ or /d/ and /t/). Bilinguals performed perceptually equivalent to the Greek and English monolinguals, suggesting that the Greek-English bilinguals have developed separate L1 and L2 phonological categories. Although this experiment did not utilize a VOT continuum to provide information on bilinguals' cutoff boundaries, it does reveal that bilinguals perceive speech sounds in a categorical manner. Additionally, the appropriate statistics were not used to analyze the data, and only a shift in the desirable direction was reported. Some research concludes that, either language mode is complicated to elicit, or the double phonemic representation does not exist.

Caramazza et al. (1973) investigated the placement of phonemic boundaries by Canadian French-English bilinguals when categorizing speech sounds in two language contexts. Participants were placed in separate French and English language modes. Like Spanish and English, French and English also have the equivalent phonetic overlap in their stop consonant VOT durations. Language mode was established by having the participants read aloud as well as having the experimenter converse with the participants before the identification task in the target language. However, English monolinguals were only exposed to English conversations and readings. Participants were asked to identify /p/, /t/, and /k/ in stimuli stop+vowel formant along a voiced and voiceless continuum (-150 to +150 ms of VOT) in two different language modes. Caramazza et al. (1973) assumed that the indication of double phonemic representation would be reflected in bilinguals' and monolinguals' phonetic boundary positioning. They assumed that phonetic boundary placements should be in agreement with the language the bilingual was using at that moment. Results revealed that bilinguals placed phonemic boundaries at intermediate VOT values compared to monolinguals' boundary placements. Bilinguals' perceptual boundaries were the same across language contexts, revealing that bilinguals were unaffected by language mode.

The findings of Caramazz et al. (1973) suggest that bilinguals map acoustic information onto speech categories by acoustic specifications that include the phonetic rules of both languages, in this case, French and English. This study did not show evidence of a double phonemic boundary in bilinguals; however, this may be because language context was not well established during the perceptual task. Although participants were asked to produce words or engage in conversation in French or English before the perceptual task, neither of the languages were emphasized during the judgement of speech sounds. One explanation for intermediate VOT values is that bilinguals were shifting back and forth between French and English phonetic rules in an uncontrolled manner during the perceptual task, in other words, sitting medially along the monolingual-bilingual continuum.

Williams (1977) explored the effect of language contexts on bilinguals' phonemic boundary placements and reported similar results as Caramazza et al. (1973). A voiced to voiceless synthesized continuum from /ba/ to /pa/ (-100 to +100 ms of VOT) was presented to 8 Spanish-English bilinguals in two language contexts; Spanish and English. Participants had to decipher whether the stop consonant stimuli was /b/ or /p/ by pointing to a picture of an object whose name began with that syllable. Language mode was established by way of 10-minute conversations in the language of interest, preceding the perceptual task. Results illustrated similar findings to the aforementioned study; again, bilinguals' category boundaries were at an intermediate point relative to those of monolingual listeners. Specifically, only 3 participants moved their phonemic boundary closer to the monolingual values for that language while the rest of the participants did not show perceptual boundary displacement. This suggests that some of the bilinguals were unable to perceptually separate their Spanish phonetic categories from their English phonetic categories, and instead had merged categories. Williams (1977) does not believe her findings are proof that bilinguals' double phonemic boundary is absent, but that the conditions of the experiment were unable to elicit such an effect. This is most likely due to the language of interest only being emphasized before the perceptual task and not during.

Bilinguals use context in order to perceive and produce their languages in a monolingual-like fashion. Caramazza et al. (1973) and Williams (1977) shed light on the importance of implementing a language context accurately in order to elicit a boundary shift in bilinguals. For these two studies, the primary method to establish language contexts was by interaction and readings in the language of interest prior to the perceptual task. Perhaps the bilingual brain requires consistent cueing in the language of interest throughout a perceptual task to successfully experience the effects of a language context, thus eliciting a perceptual shift.

Elman et al. (1977) demonstrated an improved method for establishing language context. They suggested that bilinguals need to remain focused on the language of interest throughout a perceptual task. Elman et al. (1977) presented participants with precursor sentences (e.g. *Escriba la palabra* ___ or *Write the word* ___) before delivery of each stimulus. The precursor sentences served as a language context that would consistently influence bilinguals' perception. The researchers hypothesized that bilinguals would use these language cues to disambiguate the language-phonetic similarities. Results of their experiment showed that bilinguals assigned identical acoustic tokens to different phonemic categories, and therefore, shifted their perception depending on the language of the sentences presented. Additionally, it showed a correlation between the magnitude of perceptual shifting and bilinguals' proficiency in their second language. The same methodology was used in subsequent studies to test the existence of the double phonemic boundary in bilingual speakers of English and Dutch (Flege & Eefting, 1987) and of English and French (Hazan & Boulaki, 1993) and similar results were found.

In a different investigation, García-Sierra and colleagues (2009) presented a velar stop consonant VOT continuum (-100 to +100 ms of VOT) to bilingual speakers of English and Spanish and monolingual speakers of English. Participants identified the VOT continuum in two language contexts in two separate experimental sessions. Language contexts were established by presenting Spanish or English sentences before stimulus presentation. Precursor sentences in the language of interest preceded stimuli 13% of the times in random order, while 87% of the times stimuli were presented without precursor sentences. This design allowed Garcia-Sierra and colleagues (2009) to investigate if the acoustic history of the precursor sentences affected the perception of the following speech token; especially for the stimuli near or at the phonetic boundary. The results revealed that bilinguals' category boundaries shifted toward the negative VOT end of the continuum in Spanish mode and the positive VOT end of the continuum in the English mode. Additionally, a small boundary shift was observed in bilinguals, but not in monolinguals, that was not the consequence of the acoustic history in the precursor sentences. In concordance with aforementioned studies, the degree of shift in bilinguals' phonetic boundary correlates with bilingual proficiency. Therefore, these results suggested that bilinguals' phonetic judgments were done by accessing relevant linguistic / lexical information from the precursor sentences as opposed to participants' decisions being biased due to the acoustic history of neighboring precursor sentences (Diehl et al., 1978; Eimas & Corbit, 1973; Holt & Lotto, 2002).

Precursor sentences or precursor words have been used to establish language contexts in bilinguals during speech identification tasks (Caramazza et al., 1973; Williams, 1977; Elman et al., 1977; García-Sierra, Diehl, & Champlin, 2009). In experimental designs of this nature, bilinguals have an advantage over monolinguals since they weigh the phonetic attributes in the speech stimuli when presented in two familiar linguistic contexts. Monolinguals' phonetic decisions, on the other hand, are made by weighing the phonetic attributes in the speech stimuli during a familiar linguistic context and during an unfamiliar linguistic context. Therefore, the linguistic content in each of the language contexts is processed differently between groups and might induce stimulus effects not comparable between monolinguals and bilinguals. Only one investigation has tested monolinguals and bilinguals in language contexts that are familiar to both groups. Notably, Gonzales and Lotto (2013) designed an experiment using pseudowords as stimuli to establish a language context, specifically, an English context versus a Spanish context, to test if bilinguals have language-specific phonetic systems. To do so, Gonzales and Lotto (2013) created a bilabial VOT continuum ranging from "bafri" to "pafri." The ending "ri" portion had either a Spanish or English pronunciation in order to create the two phonetic contexts (i.e., Spanish /ɾi/ or English /ɹi/). The Spanish /ɾ/ and English /ɹ/ have the identical alveolar place of articulation, but the former is produced as a tap, whereas the latter is an approximant; resulting in different sound qualities. The stimuli were presented auditorily and participants had to select on a computer screen if they heard a /b/ or /p/ speech sound from the “bafri” or “pafri” pseudoword choices. Using a between-participants experiment, monolinguals and bilinguals were exposed to Spanish or English conditions. Results showed that, when bilinguals were placed in an English context, their perception shifted to that similar of English monolinguals, while in the Spanish context, they shifted their perception in a Spanish-like way. Monolinguals, on the other hand, did not show any shift in perception. Gonzalez, Byers-Heinlein, and Lotto (in press) repeated this experiment with French-English bilinguals using French or English pronunciation of pseudowords to establish a context where shifts in perception for bilinguals were also noted.

Casillas and Simonet (2018) studied late Spanish-English bilinguals’ perception of a /b/-/p/ acoustic continuum ranging from 60 to -60 ms of VOT in 10 ms increments. They replicated Gonzales and Lotto (2013) bilabial VOT continuum of “bafri” to “pafri” with the same manipulation of pronunciation, creating a “Spanish” continuum and an “English” continuum. Results revealed that later learners of Spanish, whose native language was English, displayed a perceptual shift when in a Spanish condition versus an English condition. Simultaneous Spanish-English bilinguals also showed a shift in perception which was more pronounced than the late learners. These results expand upon those of Gonzales and Lotto (2013) in thatthey also tested whether bilinguals demonstrate a boundary effect when both languages are activated in a “bilingual” mode, or rather, how fast bilinguals can move along the monolingual-bilingual continuum. To test how simultaneous and sequential bilinguals manage to shift in and out of English and Spanish, one Spanish and English mixed continua of -40 ms to 40 ms in 10 ms increments, was presented to the participants. This /b/-/p/ continuum was utilized for both conditions. Early bilinguals were able to display a shift in perception as a function of the language block being presented, however, second-language learners were not as capable. A vital interaction was that of language mode and proficiency in Spanish; more proficient bilinguals could display a shift in perception compared to less proficient bilinguals.

This study provides evidence that proficient bilinguals need only limited phonetic input to initiate a shift in perception. Further, with the presentation of stimuli containing two language modes, we can infer that bilinguals can quickly switch between their languages of interest with only a few phonetic cues. Casillas and Simonet (2018) provide insight on the speech at which bilinguals can shift their boundaries and the limited phonetic input required for bilinguals to change between their two processing modes. This rapid recalibration is also indicative of bilinguals' enhanced attentional resources as the cognitive structures for modulating perceptual categorization may be used for other cognitive tasks such as inhibition of nonlinguistic material or tasks utilizing executive functioning.

**Studies of effects of normal nature on perceptual tasks**

Previous researchers have explored if the change in the labeling of a phoneme is the result an auditory effect of normal nature, like that of a contrastive mechanism that relies on previous acoustic information in order for auditory perception to be organized. Bohn and Flege (1993) suggested that language contexts could produce different patterns of range effects which would naturally explain a more English-like voicing boundary for Spanish-English bilinguals. Again, however, these shifts are generally much smaller than the phonetic distance between the languages' different voicing boundaries. This account would also predict shifts of equal magnitude between monolinguals and bilinguals. Likewise, a study by Brady and Darwin (1978) found range effects to be present during their perceptual task. They presented 5 blocks of 5 continuous VOT steps (5 continua of /dai/ to /tai/) in 40 trials. Results showed that English monolinguals' voicing boundaries shifted to maintain a more central position on each of the voicing continua. Though small, range effects were evident and were found to be nonlinguistic, rather than an effect of normal nature.

In addition to range effects, contrast effects also have been identified as a reason why perceptual shifts exist. Diehl and colleagues (1978) produced contrast effects by presenting one of the endpoints of the VOT continua /bae-pae/ more often than the rest of the stimuli. Participants shifted their boundary to the repetitive stimulus' side, mirroring a phonetic boundary shift. For example, when more voiceless stimuli are presented, then more voiced will be heard. Even when other properties of the speech sound are manipulated, this effect still occurs. Again, this effect is nonlinguistic in nature; a result of a general auditory processes where the ongoing auditory information is contrasted with previous acoustic information. In the present investigation, we were able to reduce auditory contrastive mechanisms by omitting carrier phrases that could affects the perception of subsequent acoustic information. The only acoustic information intended to effect perception were the stimuli itself.

Keatings and colleagues (1981) explored why bilinguals may be more susceptible to range effects. They recorded Polish productions of stop consonants and found there was not an overlap in the VOT durations of /b/ and /p/. A substantial amount of prevoicing occurred for /b/ while only short-lag VOT occurred for /p/ productions. More specifically, there was a gap in productions occurring between - 25 ms and 0 ms of VOT. The observation of a gap is also consistent with other romance languages. On the contrary, English speakers had VOT productions that were narrowed; short-lag VOT for /b/ occurred very close to long-lag VOT productions for /p/. Incredibly, these speech sounds could still be easily discriminated despite these narrowed productions.  Therefore, when bilinguals are presented with speech sounds occurring in the -25 ms to 0 ms VOT range, they are forced to place a boundary on these sounds, even though this boundary is not normally present.  This situation creates range effects, and listeners will often divide a speech continuum in two equal halves, resulting in different boundary placements (Keating et al., 1981).  In the present study, range effects were controlled for by providing stimuli in this nonexistent VOT range, essentially narrowing the range of the speech sound continua.  Most importantly, stimuli in this range was only used to provide context and the participants were not expected to categorize these speech sounds.

In this current investigation, bilinguals demonstrated a perceptual shift that was found to be linguistic in nature as opposed to the result of normal auditory mechanisms (non-linguistic). The investigation was controlled, with well-established phonetic contexts occurring in two languages of interest; Spanish and English. An interesting finding was bilinguals' ability to better attenuate to the perceptual task, evidenced by their increased behavioral responses and consistency among conditions. We propose that this may be due to bilinguals' ability to better accommodate attentional resources for a perceptual task.

Cognitive control differences between monolinguals and bilinguals do exist, the main difference being bilinguals have enhanced executive control networks compared to monolinguals.  Since the human brain has highly integrated pathways and structures, it becomes clear that activations of one domain, like language selection, can cause changes in other domains responsible for processes outside of language; such as attention control (Bialystok, 2008). The cognitive processes that bilinguals' hold superior to monolinguals are located in the frontal lobe regions, the area of the brain responsible for executive function.  Specifically, these cognitive processes are for controlling attention, shifting set, and inhibiting distraction (Bialystok, 2010).

Bilinguals are often able to demonstrate less interference on tasks than monolingual participants (Luk, De Sa, & Bialystok, 2011). When the perceptual task requires a good deal of monitoring resources, it seems that bilinguals outperform monolinguals.

The present investigation implements a Go/No-Go task where participants must either choose to respond or not respond to the stimuli. In this case, participants only label stimuli as /p/ in the Spanish phonetic context, or /b/ in the English phonetic context. These tasks require inhibition during perceptual decision making (Gomez, Ratcliff, & Perea 2007). Go/No-Go tasks require the presented signals, the acoustic stimuli, to be constantly monitored by the participants, along with consistent updating and inhibiting of the behavioral responses they are providing. Participant responses in our investigation are also a means of determining executive function differences between monolinguals and bilinguals.

In our study, monolinguals' perception changed when using their left hand to give phonetic judgements. This phenomena was perhaps due to monolinguals' decreased inhibitory control, as well as other executive abilities, in comparison to bilinguals. Monolinguals' use of their non-dominant hand appears to have affected their ability to categorize the stimuli quickly and efficiently. On the contrary, bilinguals were possibly better able to categorize during the perceptual tasks as a function of their increased executive control, yet handedness did not matter. This is indicative of the bilingual advantage; bilinguals consequently have a more robust system allowing them to focus on relevant cues and reframe from distraction (Bialystok, 2011). Bilinguals may have been more able to perform perceptual tasks with their non-dominant hand as opposed to monolinguals. We investigate how handedness plays a role in monolinguals' and bilinguals' responses amidst exploring the bilinguals' perceptual shift.

## Study Overview

Our experiment aims to explore the conditions that propel bilinguals' double phonemic boundary. Language contexts or phonetic contexts have been reported to affect bilinguals' phonetic boundary placement (Elman, Diel, & Buchwald, 1977; Flege & Eefting, 1987; Hazan & Boulaki, 1993; García-Sierra, Diehl, & Champlin, 2009; García-Sierra et al., 2012; Gonzales & Lotto, 2013; Quam & Creel, 2017), but little effort has been made to understand if the phonetic shifts are the consequence of auditory effects of normal nature like range- or contrast-effects. The present investigation is the first to assess bilinguals' and monolinguals' speech identification functions in phonetic contexts that are familiar to both groups while controlling for auditory effects of normal nature and exploring for differences in resource allocation between groups.

We implemented a Go/No-Go task for each of the phonetic contexts, during which every background sound followed a target sound equally often, while stimulus presentation was otherwise random. This approach allowed us to explore three questions of interest. (1) Do bilinguals and monolinguals show a phonetic boundary shift as a function of the phonetic contexts?. (2) Can boundary shifts, if any, can be explained based on range- and contrast-effects?. (3) Can boundary shifts, if any, be explained by differences in resource allocation (left vs. right hand)?.

## Method

### Participants

17 Spanish-English bilinguals and 16 monolingual speakers of English, ages 18-38, participated in the study (bilingual mean age = 26.82, *SD* = 4.32; monolingual mean age = 26.64, *SD* = 2.87). The bilingual group contained 7 late learners of English and 10 simultaneous bilinguals. All participants had Event Related Potentials (ERPs) recorded at the same time as the

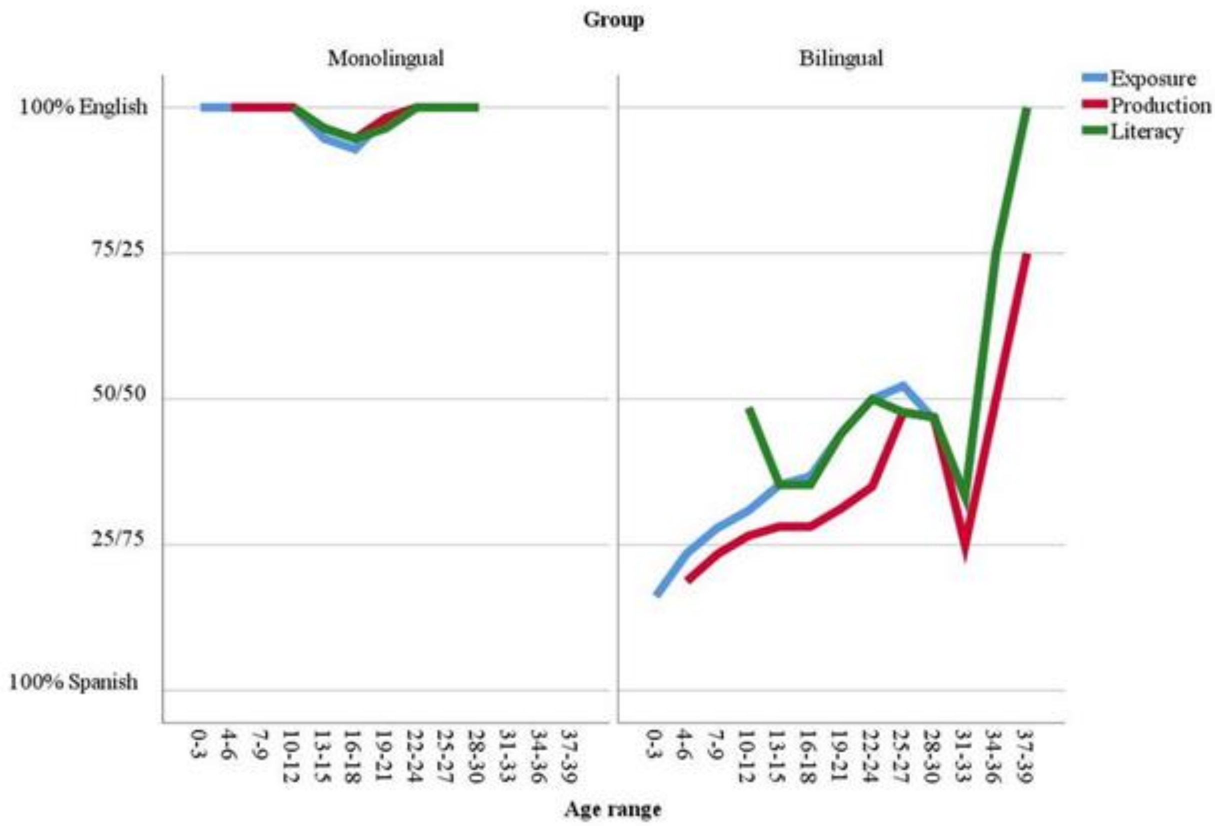
perceptual tasks, although these are not reported in the present study. Participants responded to questionnaires assessing their exposure to English and Spanish languages. All participants reported to be right-handed (using the right hand to write). From the monolingual participants, 8 were required to respond with the right hand and 8 with the left hand. From the bilingual participants, 9 responded with the right hand and 8 with the left hand.

**Language Questionnaires**

One questionnaire was administered in the study; the Language Questionnaire. The Language Questionnaire was completed by each participant to provide specific information about their level of proficiency in both Spanish and English. The questionnaire was designed to assess English and Spanish exposure and level of confidence from childhood to adulthood.

The Language Questionnaire consists of three distinct sections. Section one assessed the participants' exposure to Spanish and English in hearing, speaking, and reading. Participants answered questions about the amount of Spanish and English they were exposed to (from birth), produced (starting at 3 years old), and read (starting at 9 years old). Questions for exposure were presented on a Likert scale from 1–5 (**1** = Spanish 100%; **2** = Spanish 75% - English 25%; **3** = Spanish 50% - English 50%; **4** = Spanish 25% - English 75%; and **5** = English 100%). Section two collected information about the participants' confidence in hearing, speaking, and reading in each language starting at 9 years old. Section three contained questions pertaining to the fluency of the participants in both languages and assessed the participants' usage of English and Spanish with other people at the time of the experiment.

Figure 1. Amount of exposure, production, and literacy in Spanish and English by group



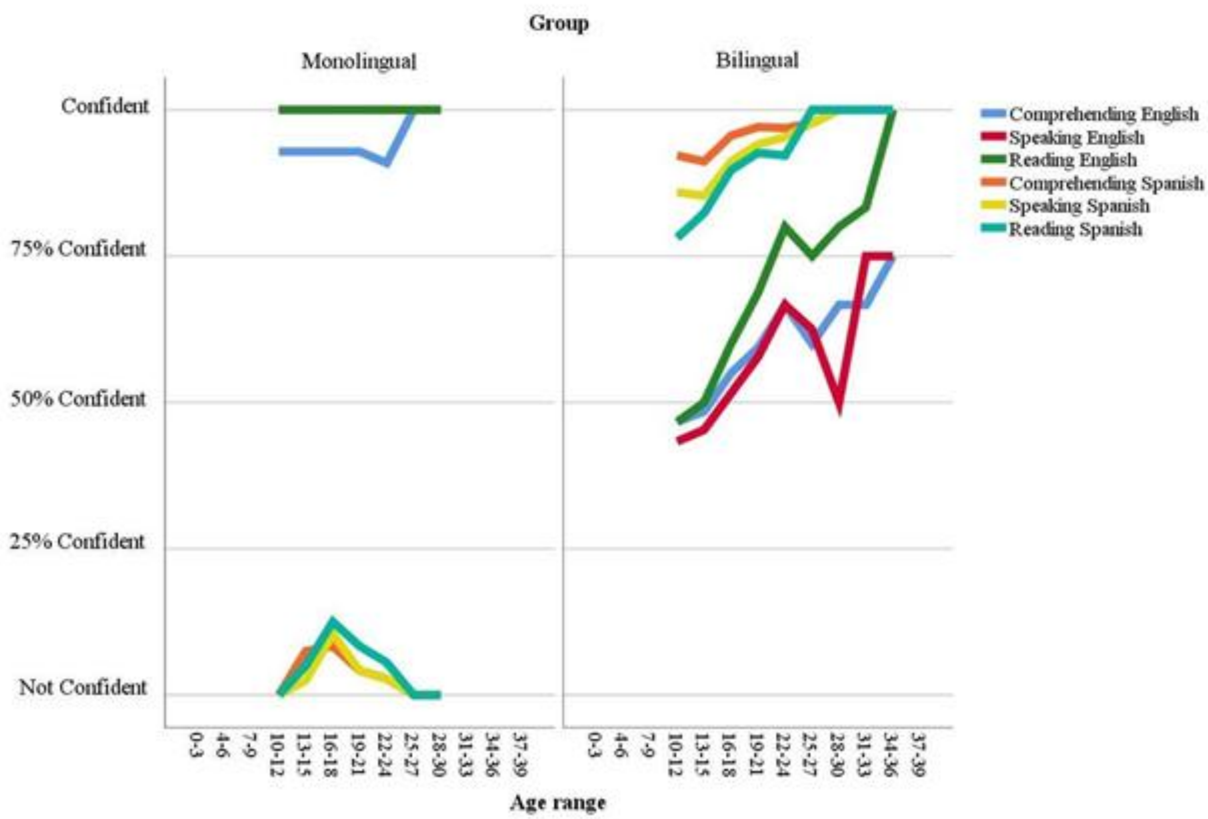

Note: Having fewer participants who were 36 or older accounts for the apparent increase in English language exposure, production, and literacy in this age range.

Figure 1 shows monolinguals' and bilinguals' average exposure, production, and literacy across the lifespan in English and Spanish. Monolingual participants' values reveal that they heard, spoke, and read English most of the time across their lives. Bilinguals' values on Figure 1 demonstrate that they heard, spoke, and read both English and Spanish across their lives, with most bilingual activity occurring during ages 22-30.

Confidence in speaking and understanding English and Spanish at the time of the experiment was assessed in bilingual participants by self-reporting their current overall confidence in speaking and understanding English and Spanish. Bilingual participants were asked to rate themselves on a 1–5 Likert scale (**1** = not confident; **2** = 25% confident **3** = 50%

confident; **4** = 75% confident; and **5** = 100% confident). The overall mean for bilingual participants' confidence in speaking was 4.35 (SD = 0.78) for English and 4.76 (SD = 0.44) for Spanish. The overall mean for bilingual participants' confidence in understanding was 4.6 (SD = 0.71) for English and 4.82 (SD = 0.40) for Spanish.

Figure 2. Amount of confidence in comprehending, speaking, and reading English and Spanish by group.




Note: Monolinguals' confidence in Speaking English (red line) is hidden behind confidence in Reading English (green line) as responses created the same contour.

Figure 2 shows participants mean confidence in comprehending, speaking, and reading both English and Spanish starting at 9 years of age. Monolingual participants are shown as having high confidence for English in comprehension, speaking, and reading, but not for confidence in Spanish. Bilingual participants have high confidence across ages for English and Spanish in comprehension, speaking, and reading. The most even distribution for Spanish occurring at ages 22 to 30.

**General Procedure**

Both monolingual and bilingual participants received hearing evaluations before beginning the study. Hearing was assessed at the frequencies of 250, 500, 1000, 2000, 4000, 6000, and 8000 hertz in each participant's left and right ears. Participants failing more than one frequency at 15 dB were excused from the experiment.

During the experimental session, participants' behavioral responses were assessed in two phonetic contexts. Behavioral responses were recorded by participants pushing a button when perceiving the sounds of interest. All participants were right-handed. Half of the participants were instructed to press the button with their right hand and the other half were instructed to use their left hand.

**Stimuli.** The speech continuum was generated using the cascade method described by Klatt (1980), a formant synthesizer created for the purpose of generating speech-like stimuli, allowing for all properties of the stimuli to be controlled. All speech stimuli were 305 ms in duration with a 10 ms burst, and 40 ms formant transitions. Vowel length varied from 295 to 215 ms depending on VOT duration. Vowel F0 was kept constant at 130 Hz until the last 95 ms portion of the vowel where it declined to 90Hz. A turbulent noise source of 10 ms (AF) duration with 80 dB amplitude was applied to simulate the consonant release. Formants and formant bandwidths (BW) were manipulated as described.

Formant transitions were linearly interpolated from values appropriate for a labial stop consonant (F1 = 380 Hz, BW1 = 250 Hz; F2 = 950 Hz, BW2 = 160 Hz; F3 = 1875 Hz, BW3 =

330 Hz; F4 = 3200 Hz, BW4 = 500 Hz; F5 = 3500 Hz, BW5 = 500 Hz) to values suitable for vowel /a/ (F1 = 790 Hz, BW1 = 130 Hz; F2 = 1280 Hz, BW2 = 70 Hz; F3 = 2655, BW3 = 70 Hz; F4 = 3200 Hz, BW4 = 500; F5 = 3500 Hz, BW5 = 500 Hz).

Stop consonant changes in aspiration (from voiced to voiceless) were accomplished by delaying the energy in F1 relative to the onset of higher formants, and by applying a noise source in F2 (amplitude of aspiration or AH = 80) during the F1 cutback period. Pre-voicing was accomplished by manipulating three parameters; fundamental frequency (F0 = 130Hz), amplitude of voicing (AV = 55 dB), and amplitude of voice exciting F1 (A1V = 45 dB) during the pre-voicing period (Flege & Eefting, 1987).

An insert earphone (EAR Tone, model 3A 10 kΩ) was used to present the speech sounds. The peak sound intensity (dB SPL) of each stimulus was measured with a sound-level meter that was connected to a 2-cc coupler. All stimuli were delivered at 74 dB peak-equivalent SPL, which is considered a comfortable listening level. Stimulus were presented using Neuroscan STIM2 software with a 4-button hardware latched response pad.

**Stimuli presentation.** Stimuli were presented using a Go/No-Go task where 3 target sounds were embedded in 6 repetitive background sounds. The target sound occurred in two distinct contexts; English and Spanish phonetic contexts. The speech continuum consisted of 15 stimuli ranging from -60 to 80 ms of VOT in steps of 10 ms of VOT. The same target sounds were presented in both phonetic contexts. The target stimuli were representative sounds of the ambiguous zone (i.e., 0, 10, and 20 ms of VOT), and the background sounds were representative sounds of non-ambiguous zones; from -60 to -10 ms of VOT for the Spanish phonetic context and from 30 to 80 ms of VOT for the English phonetic context. In both phonetic contexts, targets were presented with a probability of .18 (360 sounds) while backgrounds sounds were presented with a probability of .82 (1620 sounds). Importantly, only 3 background sounds preceded target sounds in each of the phonetic conditions. Background sounds with -30, -20, and -10 ms of VOT preceded target sounds in the Spanish phonetic condition, while background sounds with 30, 50, and 60 ms of VOT preceded target sounds in the English phonetic context. This was done so that each background sound preceded a target sound equally often. To be precise, each background sounds preceded each target sound 40 times.

The inter-stimulus interval (ISI), from the offset of the stimuli to the onset of the next stimuli, occurred in 5 possible lengths; 1210 ms, 1275 ms, 1350 ms, 1425 ms, and 1500 ms. Each of these occurred randomly, maintaining a normal distribution where 1350 ms was the most frequently presented. Each phonemic condition lasted 1 hour and consisted of 40 blocks of 48 to 51 stimuli presentations. After each block, there was a 30s resting period. Participants' responses with latencies shorter than 250 ms or longer than 1000 ms were rejected from the final average.

**Phonetic Contexts**

Two phonetic contexts were used; the Spanish phonetic context and English phonetic context. Phonetic contexts were established by exposing the participants to the phonetic properties of the language of interest during the experimental tasks. Phonetic context conditions were counterbalanced across all participants.

**Spanish phonetic context.** The perception of 3 target sounds (0 ms, 10, ms, and 20 ms of VOT) was assessed when presented within 6 Spanish-like background (i.e., background sounds with negative VOT values; -10 ms, -20 ms -30 ms, -40 ms, -50 ms, and -60 ms of VOT). Participants were instructed to press a button when perceiving a /p/ sound. To make results easier to interpret, we report /ba/ (/ba/ = 1 - % perceived as /pa/).

**English phonetic context.** The perception of target sounds (0 ms, 10, ms, and 20 ms of VOT) was assessed when presented within an English-like background (i.e., background sounds with long positive VOT values; 30 ms, 40 ms, 50 ms, 60 ms, 70 ms, and 80 ms of VOT). Participants were instructed to press a button when perceiving a /b/ sound. We report /ba/ (/ba/ = 1 - % perceived as /pa/).

## Controlling for Range Effects and Contrast Effects in the Phonetic Contexts

To control for these effects of normal nature, the same stimuli always preceded the targets. While stimuli from 0 ms to +80 ms of VOT were presented, only stimulus 30, 40, and 50 preceded the target sounds 0, 10, and 20 ms. Because of this, directly preceding stimuli did not have too large of a gap, which may have caused range or contrast effects. In the Spanish phonetic context, the same pattern was implemented; only stimuli of -10, -20, and -30 preceded the target sounds. Even after long sequences of 6 background sounds, the closer short sequence of 3 background sounds immediately preceded the targets.

## Resource Allocation Differences

When participants make changes in labelling performance between phonetic contexts and groups, this can be interpreted in two different ways. The first interpretation is that the double phonemic representation is observable. The second is that resource allocation differences may be evident between groups. This potential confound was examined by asking half of the right-handed participants to use their right hand to perform the Go/ No-Go task, while the other half used their left hand. Differences in resource allocation between groups were predicted to be similar for right-hand responders, meaning that any phonetic context-effect that was unique to bilinguals would be an indication of the double phonemic representation. Differences in resource allocation between groups were expected in left-hand responders due to the increased demands of providing perceptual responses using the non-dominant hand. We hypothesized that, if perceptual shifts exist in bilinguals in both low and high task demands (i.e., both right-hand and left-hand use), then this finding would be additional evidence in favor of a double phonemic representation.

## Results

The analyses reported include Bonferroni correction for pair-wise comparisons and planned comparisons. This is used to adjust p-values when simultaneous independent analyzes are being performed in order to reduce chances of false positive results. Greenhouse-Geisser epsilon (ε) is used for non-sphericity correction when necessary. Only interactions of interest are reported.

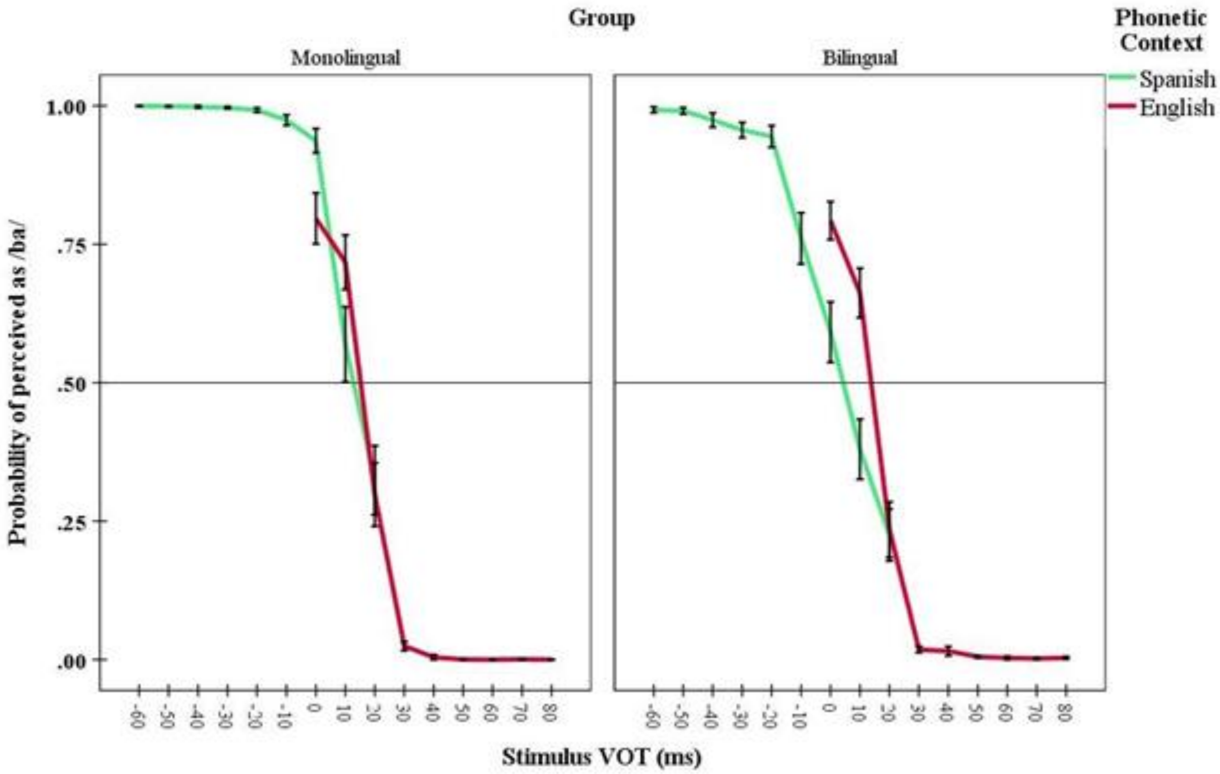
*(1) Do bilinguals and monolinguals show a phonetic boundary shift as a function of the phonetic contexts?.*

**Phonetic boundary shift and phonetic contexts**. Phonetic judgements given the 3 target sounds are reported. For ease of comparison across contexts and groups, the raw probability of perceiving /ba/ between phonetic contexts is reported for both group of participants. Statistical analyses were calculated by the number of times participants pressed the button (count responses), modeled as binomial responses. Generalized Linear Mixed Models using logit link provided analysis of these data sets.

Bilinguals, but not monolinguals, showed a phonetic boundary shift as a function of the phonetic contexts. Although monolinguals produced different results, these were found to be of nonlinguistic nature. On the x-axis, percent perceived as /ba/ is reported, despite the perceptual shift being characterized as a shift in perception from /ba/ in one context to /pa/ in another. The graph was made in this fashion to plot both context and group. For the Spanish phonetic context, a low amount of /ba/ reported in the ambiguous zone is evidence for a higher amount of /pa/

perceived. The gap seen between Spanish (green) and English (red) on the target zone is viewed as evidence for the double phonemic boundary; bilinguals showed linguistically relevant shifts in perception based on the phonetic context.

Figure 3. Phonetic boundary shift as a function of the phonetic contexts.




Note: % /ba/ reported for the English phonetic context. 1-% perceived as /pa/ is reported for the Spanish phonetic context. Participants count responses for each of the 3 target stimuli were submitted to a logistic mixed model. Error bars: +/- 2 SE. Significant interaction for Group x Phonetic Context x Target.

Table 1 below provides more detail. Significant differences were found for target stimuli of 0 and 10 ms of VOT for the monolinguals and bilingual group. Monolingual responses for stimulus 0 ms yielded higher counts of /ba/ during Spanish phonetic context in comparison to the English phonetic context. Bilinguals gave more responses as /ba/ during the English phonetic context as opposed to the Spanish phonetic context for the same stimulus. Responses for stimulus 10 ms of

VOT yielded different responses. Both the monolinguals and bilinguals gave more responses as /ba/ during the Spanish phonetic contexts than during the English phonetic context. The data discussed correspond with the difference in estimate values on the Logit scale (Table 1).

Table 1. Monolinguals and bilinguals estimated mean probabilities and estimates in logit scale for the perception of /ba/ in the Spanish and English phonetic contexts.

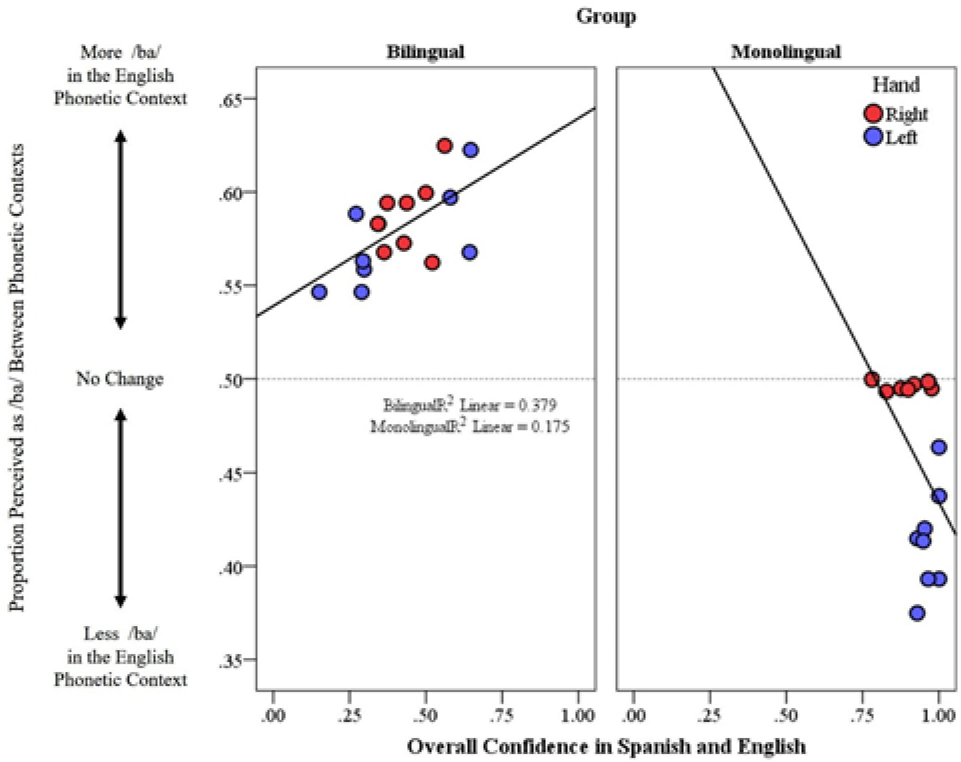
| Group | Stimulus in ms (VOT) | Phonetic Context | Mean probability | Estimate (Logit scale) | Std. Error | Estimate diff. | *p*-value |
|---|---|---|---|---|---|---|---|
| Monolingual | 0 | Spanish | 0.946 | 2.864 | *0.185* | 1.382 | ***<0.001*** |
| | | English | 0.815 | 1.481 | *0.169* | | |
| | 10 | Spanish | 0.587 | 0.350 | *0.166* | -0.657 | ***<0.001*** |
| | | English | 0.733 | 1.007 | *0.167* | | |
| | 20 | Spanish | 0.316 | -0.772 | *0.167* | 0.138 | *0.383* |
| | | English | 0.287 | -0.910 | *0.167* | | |
| Bilingual | 0 | Spanish | 0.596 | 0.387 | *0.161* | -1.014 | ***<0.001*** |
| | | English | 0.802 | 1.401 | *0.164* | | |
| | 10 | Spanish | 0.374 | -0.514 | *0.161* | -1.195 | ***<0.001*** |
| | | English | 0.664 | 0.681 | *0.161* | | |
| | 20 | Spanish | 0.215 | -1.293 | *0.163* | -0.058 | *0.449* |
| | | English | 0.225 | -1.235 | *0.163* | | |

**Phonetic boundary shift and language experience.** Past research has revealed a correlation between phonetic boundary shifts and amount of second language experience. The relationship was explored using the estimate values in Logit scale for every target sound and transforming these values into predicted probabilities of pressing the button. The three target scores by each participant associated with the predicted probability of pressing the button were summed. Large values represented higher probability of perceiving /ba/ during the English phonetic context and small values meant that there was a low probability of perceiving /ba/ during the English phonetic context. Values closer to 1 were high, values closer to 0 were low, and values close to .5 were considered to represent equal probability of perceiving /ba/ between both phonetic contexts, meaning no change in perception occurred.

Language constructs associated with exposure (Figure 1) and confidence (Figure 2) were used to assess this correlation.  Higher values represented more exposure and confidence in English (i.e., values close to 5) and lower values represented more exposure and confidence in Spanish (i.e., values close to 1).

Figure 4 is a scatterplot with monolingual and bilingual perceptual responses to the target zone with hand and phonetic context reported.  Bilinguals, in this graph, show a significant positive correlation.  Those that produced the most balanced self-reports on the language questionnaire showed the largest probability increase in perceiving /ba/ during the English phonetic context for specifically 0 ms and 10 ms targets.  No significant correlations were found for target 20 ms of VOT. Monolinguals showed a nonsignificant correlation between language confidence and probability of increasing perception of /pa/ in either context.  Additionally, monolingual right-hand responders did not show a change in perception of /ba/ between both phonetic contexts.  Left-hand monolingual responders perceived less /ba/ sounds during the English Phonetic Context.  Labelling performance as a function of hand used is interpreted as evidence that monolinguals were affected by task demands.

Figure 4. Proportion perceived as /ba/ between phonetic contexts as a function of overall confidence in Spanish and English by hand.

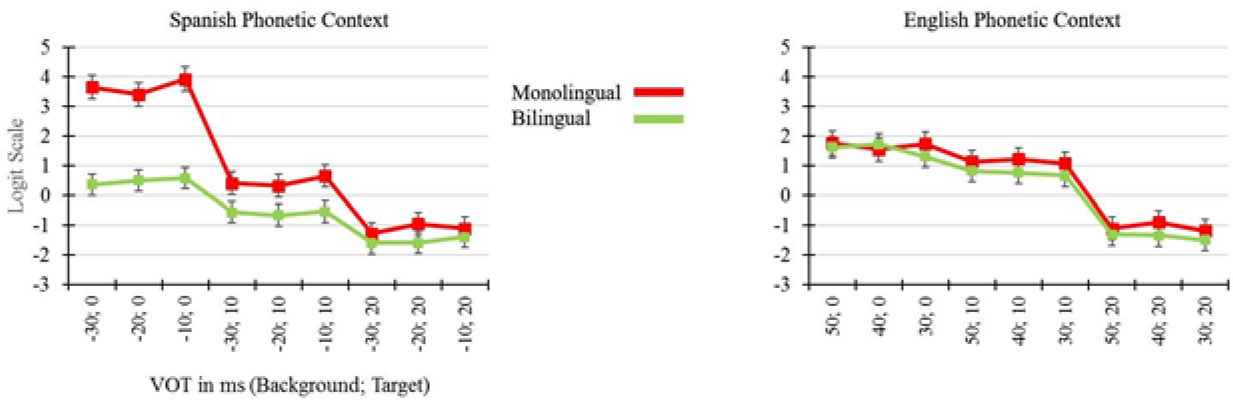



Note. Probability of perceiving /ba/ for target 0 ms of VOT between both phonetic contexts as a function of the overall confidence in Spanish and English. Confidence values closer to, or at, 0 represent confidence only in Spanish, values close to, or at, 1 represent confidence only in English, and values closer to, or at, .5 represent equal confidence for both languages.

*(2) Can boundary shifts, if any, be explained based on range- and contrast-effects?*

By comparing the phonetic judgements given to each of the target sounds when preceded by each of the 3 background sounds, we examined if the change in labeling performance in both groups was the result of auditory effects of normal nature. In other words, is a contrastive mechanism responsible for this perceptual shift? If this were to be true, then each of the background sounds preceding the target sounds would be perceived differently. We found that it did not matter which of the three background sounds precedes a target sound; they are perceived similarly, no matter the acoustic separation. If we were to have found a correlation between the background sound and the target sound in terms of distance away from each other, then we could have inferred that contrastive mechanisms are responsible for the shift in perception.

Figure 5. Estimates of the perception of target sounds in Logit scale.




Note: Estimates of the perception of target sounds in Logit scale. Estimate values of 0 represent a probability mean value of .5 and negative estimates values correspond to probability mean values less than .5. The x-*axis* shows VOT values for the target (top) and preceding background sound (bottom) in ms. Error bars ±1 S.E.

In Figure 5, the phonetic judgements for each target sound as a function of the preceding background stimuli is reported. No significant interaction was found between Group x Background x Target for the Spanish ($F(4, 576) = 2.00$, $p > .05$) or the English ($F(4, 576) = 2.15$, $p > .05$) phonetic context. Across each phonetic context and group, the percent perceived as /ba/ remained the same even though immediately preceding stimuli changed. Again, contrast-effects did not account for the phonetic boundary shift.

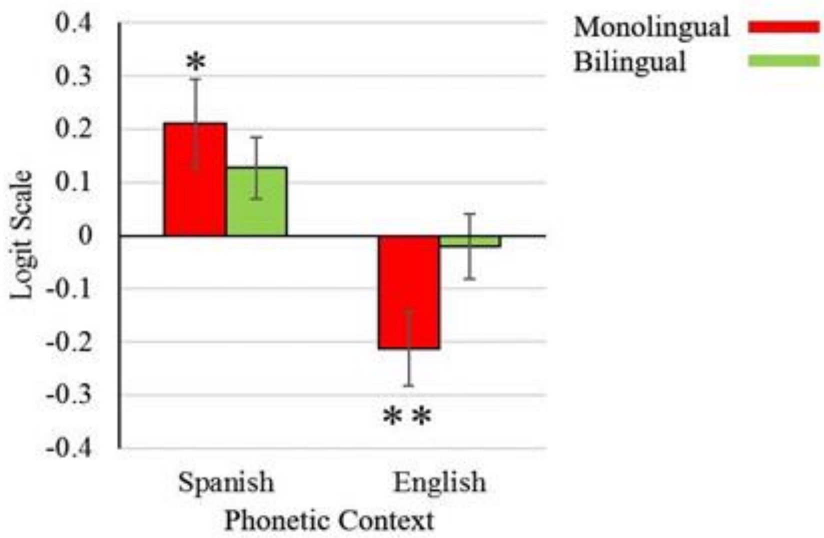
In regard to range affects, -40 ms to -10 ms of VOT are identified as VOT sounds that are most affected by experimental manipulations. This range did not contain any target sounds, so bilinguals' labeling performance was most likely not affected by these effects of normal nature. The oddball paradigm manipulated in the present study can be interpreted as the result of range-effects since target sounds are embedded in blocks of stimuli with different background sounds, as was the case in the study of Brady and Darwin (1978).

Range-effects were controlled for by presenting sequences of 3 or 6 background sounds. The number of times the participants pressed the response button for the target stimuli 0 ms, 10 ms, and 20 ms of VOT per a short level sequence of 3 background sounds or long level sequence of 6 background sounds is recorded. The results showed a significant interaction for Group x Phonetic Context x Sequence ($F(2, 1140) = 4.07$, $p = .0438$). The pair-wise comparisons revealed that monolinguals, perceived significantly more /ba/ sounds in the short sequence than in the long sequence during the Spanish phonetic context ($t(1140) = 2.55$, $p < .05$), but more /ba/ sounds in the long sequence than in the short sequence during the English phonetic context ($t(1140) = -3.05$, $p < .05$). Bilinguals' perception of /ba/ did not change between short and long sequences within each phonetic context (See Figure 6). No significant interaction was found between Group x Phonetic Context x Target x Sequence ($F(2, 1140) = .200$, $p = .820$). When collapsing the 3 target sounds together and screening for range-effects, it was found that range-effects were present for monolinguals during both phonetic contexts. Most importantly, these range-effects were not present in bilinguals.

Due to interesting hand effects noted earlier, further analysis was done to see if the range-effect found in monolinguals was due to the hand used during the perceptual judgement.

The results showed, that when collapsing the 3 target sounds, range-effects were present in monolinguals during both phonetic contexts, but range-effects were not present in bilinguals. Further analyses were performed to clarify if the range-effect found in monolinguals was the consequence of the hand used to press the response button. No significant interaction was found, along with monolinguals' change in performance during a short or long sequence during the perceptual task.

Figure 6. Stimuli sequence length by group and context.




Note. Estimate differences (short sequence minus long sequence) during the perception of /ba/ in the two phonetic contexts. Estimate values of 0 represent a probability mean value of .5 and negative estimates values correspond to probability mean values less than .5. Positive estimates represent more /ba/ sounds perceived during the short sequence and negative estimates represent more /ba/ sounds perceived during the long sequence. Error bars ±1 S.E. calculated from the estimate differences. * $p < .05$; ** p < .01

*(3) Can boundary shifts, if any, be explained by differences in resource allocation (left vs. right hand)?.*

Table 2 shows the pair-wise comparisons of interest. Monolingual left-hand responders perceived more /ba/ sounds than monolingual right-hand responders during the Spanish phonetic context. Also, monolingual left-hand responders perceived fewer /ba/ sounds than monolingual right-hand responders during the English phonetic context. Bilinguals did not show hand-effect differences between both phonetic contexts and between both sequence lengths.

Table 2. Resource allocation differences as a function of all variables

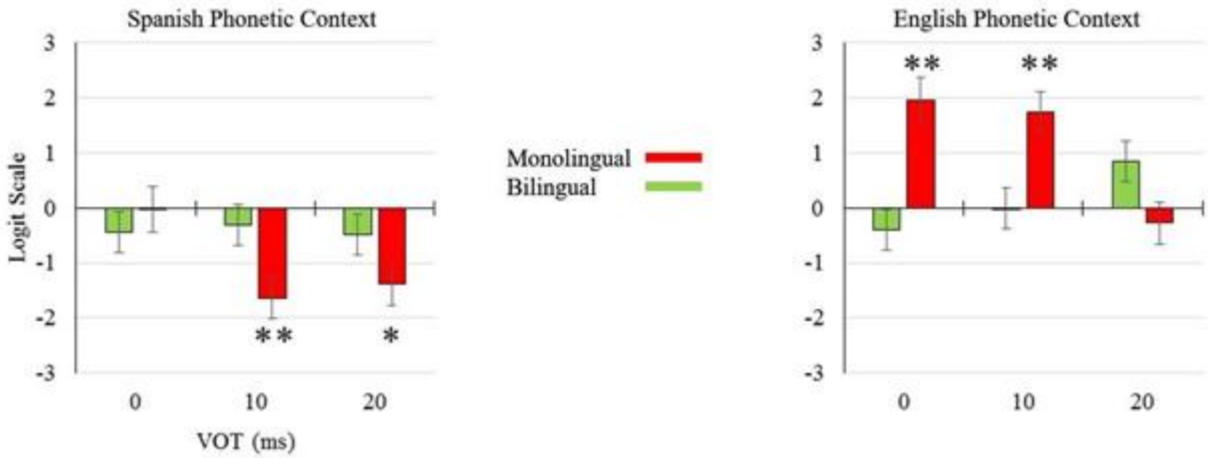
| Group | Phonetic Context | Sequence | Hand | Mean probability Diff. | Estimate Diff (Logit Scale) | Std. Error | *p* -value |
|---|---|---|---|---|---|---|---|
| Monolingual | Spanish | Short | Left vs Right | -0.192 | -0.938 | *0.384* | *0.159* |
| | Spanish | Long | Left vs Right | -0.241 | -1.099 | *0.381* | *0.055* |
| | English | Short | Left vs. Right | 0.247 | 1.084 | *0.377* | *0.058* |
| | English | Long | Left vs Right | 0.256 | 1.204 | *0.378* | ***0.026*** |
| Bilingual | Spanish | Short | Left vs Right | -0.115 | -0.480 | *0.363* | *0.363* |
| | Spanish | Long | Left vs Right | -0.080 | -0.341 | *0.363* | *0.344* |
| | English | Short | Left vs. Right | -0.033 | 0.133 | *0.364* | *0.718* |
| | English | Long | Left vs Right | -0.040 | 0.163 | *0.364* | *0.657* |

Note. Monolinguals' and bilinguals' probability differences and estimates differences in Logit Scale for the perception of /ba/ in the Spanish and English phonetic context and both sequence lengths when using left or right hand.

Resource allocation differences have been reported between bilinguals and monolinguals, therefore, we questioned if our implementation of the Go/No-Go task favored bilinguals over monolinguals. To assess this, we placed both groups in tasks that required high or low resource allocation. Again, right-handed participants were asked to make phonetic judgements when using their left hand or their right hand. We hypothesized that bilinguals, regardless of the task demands (e.g., handedness), would show similar responses between hands while monolinguals' responses would be contingent on the hand used.

Figure 5 below depicts that bilinguals' labeling performance was similar regardless of the hand used to the press the button. On the contrary, monolinguals' responses showed significant differences between hands for targets 10 and 20 ms of VOT during the Spanish phonetic context and stimulus 0 ms and 10 ms of VOT for the English phonetic context. We interpret these results as evidence that bilinguals have better ability to cope with task demands.

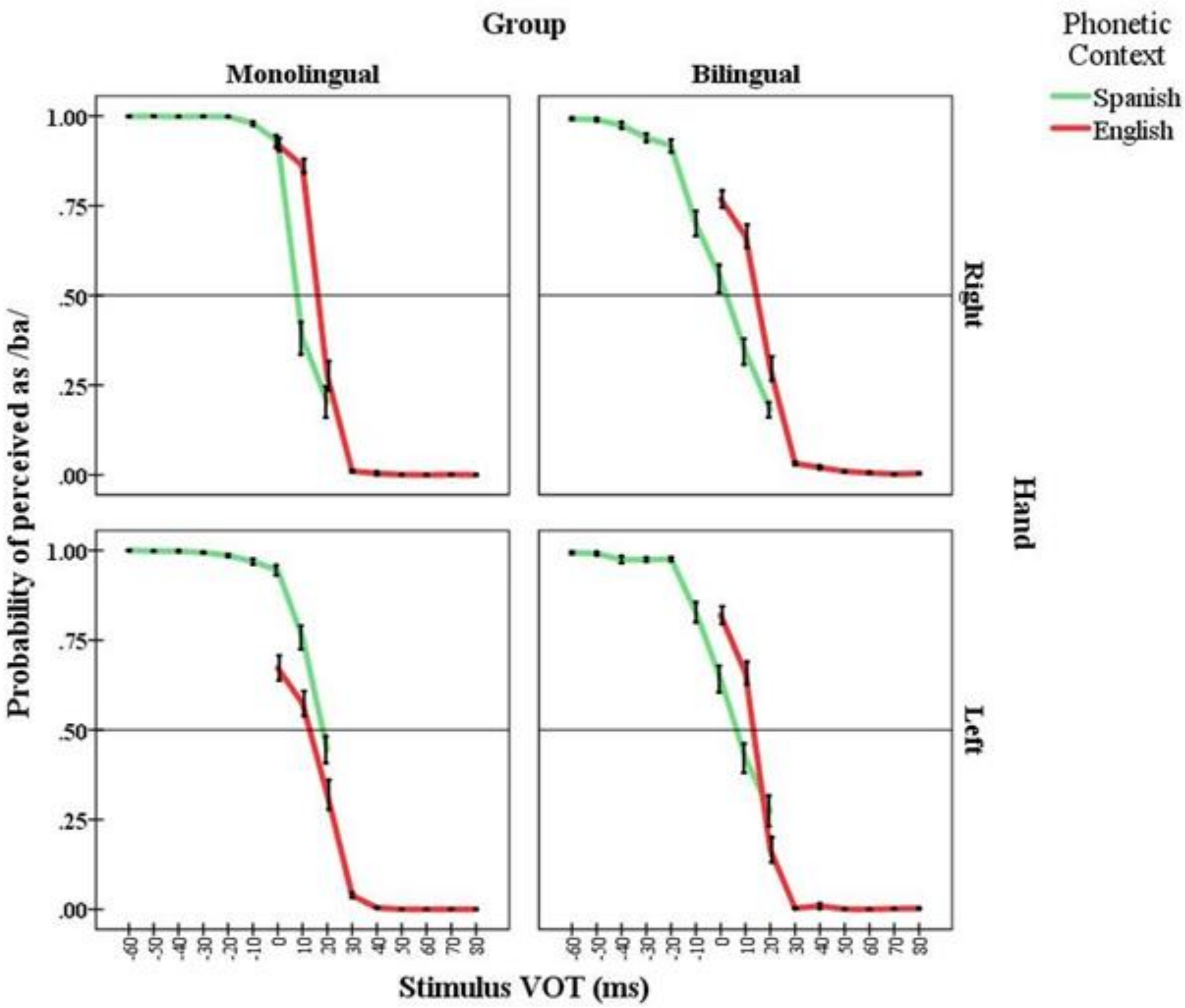
Figure 5. Estimate differences (right hand minus left hand) during the perception of /ba/ in both phonetic contexts.




Note: Estimate values of 0 represent a probability mean value of .5 and negative estimates values correspond to probability mean values less than .5. Positive estimates represent less /ba/ sound perceived when using the left hand, and negative estimates represent more /ba/ sounds perceived when using the left hand. Difference scores are compared against zero to assess statistical significance. Error bars ±1 S.E. were calculated from the estimate differences.
* $p < .05$; ** $p < .01$

To identify if hand effects were present in altering bilingual's phonetic boundary shift, the next analysis used the same logistic mixed model. Pair-wise comparison revealed that bilinguals show a change in behavioral responses corresponding to the appropriate phonetic context, no matter the hand used to press the button. Monolinguals' behavioral responses changes as a function of hand used.

Figure 6. Probability of /b/ responses by group and by context




Note: Raw probability of /b/ responses. Note: 1-% perceived as /pa/ is reported for the Spanish phonetic context. Error bars: +/- 1 SE

In Figure 6 above, the double phonemic representation is evidenced regardless of the hand used for perceptual judgement. Bilinguals perceived the targets 0 ms and 10 ms of VOT as /ba/ more in the English phonetic context than the Spanish phonetic context, unlike monolinguals. This graph represents evidence for the presence of bilinguals' double phonemic boundary during both high and low task demands. Additionally, most of the changes in labeling performance were in accordance with the appropriate phonetic context. Monolinguals perceptual shift shown in Figure 6, was a shift only present during the low task demand condition and the changes were not in accordance with the appropriate phonetic context (see Table 4 for more information).

Table 4. Mean probability differences and estimate differences in Logit scales.

| Group | Target | Hand | Phonetic Context | Mean probability Diff. | Estimate Diff (Logit Scale) | Std. Error | *p*-value |
|---|---|---|---|---|---|---|---|
| Monolinguals | 0 | L | Spanish vs. English | 0.270 | 2.171 | *0.158* | ***<.0001*** |
| | | R | Spanish vs. English | 0.010 | 0.180 | *0.173* | *0.302* |
| | 10 | L | Spanish vs. English | 0.193 | 0.893 | *0.101* | ***<.0001*** |
| | | R | Spanish vs. English | -0.494 | -2.479 | *0.119* | ***<.0001*** |
| | 20 | L | Spanish vs. English | 0.131 | 0.559 | *0.097* | ***<.0001*** |
| | | R | Spanish vs. English | -0.091 | -0.550 | *0.127* | ***<.0001*** |
| Bilinguals | 0 | L | Spanish vs. English | -0.184 | -1.000 | *0.112* | ***<.0001*** |
| | | R | Spanish vs. English | -0.226 | -1.035 | *0.096* | ***<.0001*** |
| | 10 | L | Spanish vs. English | -0.251 | -1.033 | *0.098* | ***<.0001*** |
| | | R | Spanish vs. English | -0.323 | -1.341 | *0.092* | ***<.0001*** |
| | 20 | L | Spanish vs. English | 0.108 | 0.679 | *0.116* | ***<.0001*** |
| | | R | Spanish vs. English | -0.115 | -0.652 | *0.104* | ***<.0001*** |

Note: Probability and Estimate differences represent Spanish context minus English context during the perception of /ba/ when using the left or the right hand. Negative probability and estimates values represent the expected direction (i.e., less perception of /ba/ in the Spanish phonetic context than in the English phonetic context). Difference scores are compared against zero to assess statistical significance. Standard errors were calculated from the estimate differences.

## Discussion

This research study was constructed with the purpose of identifying the double phonemic boundary shift in bilinguals using a new methodology while also controlling for the effects of normal nature. Methodology consisted of using a bilabial VOT continuum of Spanish and English speech sounds to elicit a phonetic shift free of range- and contrast-effects. We tested this by placing Spanish-English bilinguals in two phonetic contexts and measuring their ability to discriminate between English and Spanish speech sounds located in the phonetic overlap. These speech sounds have a phonetic overlap yet contain different phonemic-meaning depending on properties of the language of interest presented. We analyzed how monolinguals' and bilinguals' phonetic judgements are shaped by the Spanish phonetic context versus English phonetic context, and further, how these phonetic judgements may be indicative of bilinguals' enhanced attentional demands. The discussion is outlined to cover three main questions.

*(1) Do bilinguals and monolinguals show a phonetic boundary shift as a function of the phonetic contexts?.*

The gap found in the bilinguals' panel in Figure 3, an occurrence of significant interaction, is taken as evidence for the double phonetic boundary shift, as labelling performance changed depending on the phonetic information offered. Our results support the argument that bilinguals use two language-phonetic systems to interpret linguistic input and distinguish between ambiguous acoustic material (Elman et al., 1977; & Gonzales & Lotto, 2013). Bilinguals perceived target sounds /b/ less in the Spanish phonetic context than in the English phonetic context, indicating that the categorical shift was in the expected direction.

Results also aligned with previous findings that the degree of the double phonemic boundary is correlated with language experience (Elman et al., 1977; Garcia-Sierra et al., 2009, Casillas & Simonet, 2018; Best & Tyler, 2007) and independent from monolinguals' perceptual trends. Bilinguals with similar confidence levels between Spanish and English demonstrated the strongest categorical shift in the predicted direction. This was achieved by perceiving phonetic contrasts differently depending on the context in which they were placed. These bilinguals perceived the most /ba/ sounds during the English phonetic context than during the Spanish phonetic context. This corresponds to previous research that early sequential bilinguals or early simultaneous bilinguals exhibit this ability to change their perception with limited linguistic input (Antoniou, Tyler, & Best, 2012). This is also in line with Best and Tyler (2007), as bilinguals with equal experience in both languages are hypothesized to develop separate L2 phonetic categories for their second language phones. Bilinguals were able to become sensitive to the different L1 and L2 phonetic realizations of same acoustic phonetic event, in this case Spanish and English realizations of /b/.

On the other hand, bilinguals who learned their second language later in life, and in turn had mismatched confidence levels in their two languages, may have been discriminating phonetic contrasts with L1 and L2 merger, as PAM-L2 described, leading to fewer phonetic contrasts accurately perceived. Nevertheless, this study supports that bilinguals' phonetic boundary shift is the direct result of their experiences and knowledge with both the Spanish and English languages during some point in their life.

Monolinguals' responses indicated that the double phonemic boundary shift is a bilingual-only effect, as they showed a change in labeling performance that was mixed for phonetic contexts. Target stimulus 10 ms of VOT was perceived in alignment with the phonetic context. On the contrary, 0 ms target was perceived in accordance with the phonetic context, "accordance" meaning that the phonetic contrast was perceived according to the language of interest. Unlike bilinguals' boundary shift, we suggest monolinguals' shift in perception was nonlinguistic in nature, as categorization patterns could not be attributed to a language-specific phonetic shift. A contrastive mechanism is likely to blame in monolinguals' shift in labelling performance across contexts (Brady & Darwin, 1978; Diehl et al., 1978). The observed finding was explored to determine if range-effects, contrast-effects, and differences in resource allocation between monolinguals and bilinguals are to blame as opposed to the double phonemic representation.

*(2) Can boundary shifts, if any, be explained based on range- and contrast-effects?.*

Diehl and colleagues (1978) produced contrast effects by presenting one of the endpoints of the VOT continua /bae-pae/ more often than the rest of the stimuli to test whether or not preceding acoustic information serves as a contrastive anchor that modifies participants' perception during a perceptual task. They proposed that this contrastive mechanism is nonlinguistic in nature since this same phenomenon is not only seen for speech sounds, but during the categorization of non-speech sounds (Holt et al., 2000; Holt & Lotto, 2002; Lotto et al., 1997; Lotto & Kluender, 1998). Further, this shift is replicated in non-human species to solidify that humans do not have additional auditory mechanisms related to language, but that effects of normal nature may be present among all acoustic stimuli. In the present investigation, we reduced auditory contrastive mechanisms by omitting carrier phrases during the establishment of phonetic contexts, acoustic input that could have affected the perception of subsequent acoustic information. Our methodology only allowed for the perception of ambiguous stimuli to be mainly affected by the stimuli itself, as opposed to additional lexical and language input.

Stimuli was meticulously constructed so that target stimuli was only directly preceded by 3 background stimuli within 30 ms of VOT of the target zone (e.g. -30 ms, -20 ms, or -10 ms of VOT for the Spanish phonetic context or 30 ms, 40 ms, or 60 ms of VOT for the English phonetic context). Contrast-effects disappear when background stimuli are closer to the target stimuli zone (Diehl et al., 1978). In other words, since background stimuli did occur farther away from the target zone (at the endpoints of the stimuli range), contrast effects were reduced. Statistical analyses confirmed that labeling performance for target sounds 0 ms, 10 ms, and 20 ms of VOT did not change as a function of the immediately preceding background sound, as no significant reaction existed between Group x Background x Target x Phonetic Contexts.

Range-effects were proposed by Bohn and Flege (1993) as an explanation for the perceptual shift found via language contexts. Brady and Darwin (1978) found these effects to be a non-linguistic phenomenon, as participants divided their continuums of perceptual stimuli into two equal halves, where boundaries were shifted to maintain a central position on the continuum. The oddball paradigm in the present study, implemented via a Go/No-Go task, was predicted to reduce range-effects. Since the continua presented during the current study vary in order of stimuli as well as distance away from target stimuli, they did not fall subject to perceptual changes as a function of the continuum order.

To reiterate, the present study used -30 ms, -20 ms, or -10 ms of VOT background stimuli to precede the target sounds for the Spanish phonetic context. By integrating this range into the background stimuli, it was anticipated that bilinguals' susceptibility to range effects would dissipate. Keatings and colleagues (1981) explored bilinguals' susceptibility to range effects by recording Polish productions of stop consonants and found that there is substantial amount of prevoicing for /b/ while only short-lag VOT occurred for /p/ productions, more or less displaying a gap in productions occurring between -25 ms and 0 ms of VOT, a VOT space consistent with other romance languages. It is assumed then, that the only information speakers of romance languages need to distinguish voiced from voiceless stops is whether the VOT value is positive or negative. In the present investigation, by implementing productions within this range that are not bound by phonemic constraints into our VOT continuum, the perceptual task was better manipulated. Monolingual English speakers in Keatings et al.'s (1981) study had voiced and voiceless stop consonant categories, so discrimination of these consonants happened precisely. Therefore, the phonetic boundary shift in our investigation may potentially be the consequence of range-effects, instead of bilinguals' double phonemic representation.

*(3) Can boundary shifts, if any, be explained by differences in resource allocation (left vs. right hand)?.*

As previously mentioned, employment of the Go/No-Go task was used to reduced range- and contrast-effects while simultaneously assessing the presence of bilinguals' double phonemic boundary. Another factor in bilinguals' and monolinguals' performance during the perceptual task was resource allocation. It is thought that high-level cognitive control processes are required to inhibit the non-target language during perceptual tasks, thus demonstrating attentional resource allocation. These control processes are assumed to be engaged during other tasks like attentional control tasks (Kousaie & Phillips, 2012). Attentional control tasksinclude inhibition of irrelevant information, selective attention to target information, and switching (Bialystok, 2004). Bilinguals must utilize their inhibition skills daily, and therefore extensively practice their control mechanisms, so a less efficient control process could be presumed in monolinguals. In this case, the change in labeling performance between the Spanish and English contexts could not be evidence for the double phonemic representation but the enhanced mechanisms bilinguals have to cope with task demands.

Right-handed participants were recruited to explore the resource allocation versus double phonemic boundary dilemma. Half used their dominant hand while the other half used their non-dominant hand during the Go/No-Go task. Left-hand responders were postulated to have increased difficulty in task demands between groups because of the employment of the non-dominant hand, while similarities could be seen between groups for the right-handed responders. It was hypothesized that both right- and left-hand bilinguals would show a perceptual shift in accordance with the phonetic context during testing, not explained by hand use. On the contrary, when changes in labeling performance occurred in monolinguals in accordance with language context, differences in task demands would be responsible.

The present study revealed that bilinguals labeling performance was not different between bilingual right-hand responders and bilingual left-hand responders. This suggests that, regardless of task demands, bilinguals were able to allocate resources in similar ways. However, monolinguals' labeling performance was impacted by hand effect and was different depending on hand used within phonetic contexts. Monolinguals perceived more /ba/ sounds with their left hand during the Spanish phonetic context, while in the English phonetic context, their right-hand counterpart perceived less /ba/ speech sounds. Monolinguals' hand effect can be explained by their decreased inhibition, as the monolinguals could not keep up with task demands and were not fast enough to press the response button, leading to overall decreased responses to target sounds. More specifically, monolinguals had fewer responses compared to bilinguals in both phonetic contexts. Forcing monolinguals to use their non-dominant left hand presumably caused increased task demands, making monolinguals overall less accurate than bilinguals, since this drop occurred in both conditions. Bilinguals did not show a similar pattern, as hand-effects were not evident. Additionally, accuracy was similar across hands, most likely a result of enhanced executive functions due to the experience managing two languages.

It is important to note that no previous research to date has tested whether monolinguals in particular could have hand-effect differences affecting their non-dominant hand due to a higher cognitive load, especially during perceptual tasks. It seems many studies which employ hand use to make a judgement either do not report differences in hand or require participants to use their preferred hand (Foy & Mann, 2014; Jiao, Liu, Wang, & Chen, 2017; Emmorey, Luk, Pyers, & Bialystok, 2008). We propose the idea that monolinguals are less apt at managing a higher cognitive load due to incongruency between their dominant and non-dominant hand responses during a perceptual task. Supporting this interpretation, previous research has shown that bilinguals are often able to demonstrate less interference on their tasks compared to monolingual participants (Luk, De Sa, & Bialystok, 2011). Therefore, this observed inequality between monolinguals' and bilinguals' resource allocation may be able to explain the results of our study.

It was Elman and colleagues (1977) who proposed that higher-level linguistic mechanisms are responsible for categorizing speech sounds, such as stop voicing contrasts, based on previously heard acoustic information. We presume that our results also provide evidence for the top-down processing of linguistic information, in order to explain how bilinguals can change their perception based on the acoustic stimuli. Further, this highlights the intricacies of the speech processing mechanism and emphasizes the complicated processes that occur for speech signals to be perceived accurately.

In sum, we believe in the existence of the double phonemic representation by means of language experience, based on the results of our study. Only phonetic information could have caused this sort of perceptual shift, not evident in Gonzales and Lotto (2013), Gonzales and colleagues (in press), and older studies that used language contexts to elicit a shift. Moreover, VOT was the only differentiating factor. Pseudoword lexical influences were apparent in these studies. Lexical and language cues were not provided in the study in order for the phonetic context to be isolated. It was found that, phonetic influences are enough to permeate the brain in an English and Spanish mode causing relevant shifts in specific directions, not related to auditory effects of normal nature. Bilinguals' phonetic shift is not the effect of changes in perceptions due to previously heard acoustic information. Even when no lexical or syntactic information is present, bilinguals rely on their own language-specific phonetic systems and access to higher-level linguistic information to discriminate acoustically ambiguous material. The results of our study support the idea that bilinguals develop a double phonemic representation for the same phonetic sound as a result of their experiences with two languages.

## Limitations

Limitations include issues with the bilingual participant group. The bilingual group consisted of 7 late learners of English, with the subsequent 10 being considered simultaneous bilinguals. In other words, this group was comprised of more that one type of bilingual (i.e., late L2 learner, early sequential bilingual, or simultaneous bilingual). Many studies have revealed that late learners of a second language often show less pronounced perceptual shifts between language contexts as well as diminished executive function advantages (Elman, et al., 1977; García-Sierra et al., 2009; Luk, De Sa, & Bialystok, 2011; Casillas & Simonet, 2018).

Additionally, while a main proportion of this study focused on hand-effects, no formal measures of handedness were completed on the individuals.

## Conclusion

The present investigation provides evidence for Grosjean's language mode framework, and language modes were used to discriminate between phonetic information. This investigation yielded three main outcomes: (1) The English and Spanish phonetic contexts produced an effect on the placement of the phonetic boundary, a perceptual shift in accordance with the language of interest; a phenomenon that was only present among bilinguals regardless of the hand used for behavioral responses. (2) Bilinguals' boundary shift was correlated with their confidence in comprehending, speaking and reading both languages. (3) Bilinguals' perceptual shift was not the consequence of contrast-effects or range-effects, but rather due to a shift that was linguistic in nature.

More broadly, this research study provides insight on the complexity of speech processing and the saliency that language experiences have on the future of our perception. With this information, we can further appreciate the differences monolinguals and bilinguals exhibit in perceptual tasks and continue to study the ways in which these differences may manifest themselves in all areas of cognition.

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