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Costs and Cues in the Auditory Comprehension of Code-switching

by

Alice Shen

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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in

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of the

University of California, Berkeley

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Professor Susan Lin

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Summer 2020

# **Costs and Cues in the Auditory Comprehension of Code-switching**

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Alice Shen

## Abstract

## Costs and Cues in the Auditory Comprehension of Code-switching

by

Alice Shen

Doctor of Philosophy in Linguistics

University of California, Berkeley

Professors Keith Johnson and Susanne Gahl, Co-chairs

Bilinguals alternate frequently between languages, but many psycholinguistic studies on code-switching have reported a “switch cost”, i.e. an increased processing difficulty, in production (Meuter & Allport, 1999; Thomas & Allport, 2000; Costa & Santesteban, 2004; Gollan & Ferreira, 2009, although see Kleinman & Gollan, 2016), recognition (Soares & Grosjean, 1984), and comprehension (Olson, 2017). This dissertation involves three experiments investigating the factors modulating switch cost in the auditory comprehension of Mandarin and English code-switched words. First, recent research suggests that subtle phonetic differences between the pronunciation of code-switched utterances and unilingual utterances might act as anticipatory cues to code-switches for listeners (Piccinini & Garellek, 2014; Fricke, Kroll & Dussias, 2016), which could mitigate switch cost. Second, an “asymmetric switch cost,” or higher switch cost for the dominant first language (L1) compared to the second language (L2), has been reported for auditory comprehension of Spanish-English code-switches (Olson, 2017). Additionally, Mandarin-English bilinguals judge switches from English-to-Mandarin as infrequent compared to Mandarin-to-English switches (Lu, 1991; Ong & Zhang, 2010). Thus, Mandarin-English switching could be subject to a cost asymmetry driven not just by dominance but by frequency.

Experiments 1 and 2 test the effects of withholding anticipatory phonetic cues on code-switched recognition by splicing English-to-Mandarin code-switches into unilingual English sentence contexts. Experiment 1 measured Mandarin-English bilinguals’ (N=42) reaction times in a concept monitoring task where they had to press a button when they heard a pictured object mentioned in an auditorily presented English sentence. The target word was either code-switched (i.e., in Mandarin) or unswitched. RTs were slower when the target was a code-switch, suggesting a switch cost. Experiment 2 tracked Mandarin-English bilinguals’ (N=41) eye movements during a task in which they were asked to fixate on the pictured object in a display that matched a code-switched (Mandarin) or unswitched target word in an auditorily presented English sentence. The average proportion of all participants’ looks to target pictures corresponding to sentence-medial code-switches decreased when cues were withheld, suggesting that withholding anticipatory phonetic cues can negatively affect code-switched recognition. Therefore, in normal conditions, bilingual listeners use phonetic cues to anticipate an upcoming code-switch. Acoustic analysis of stimuli from Experiments 1 and 2 showed tone-specific

anticipatory pitch coarticulation prior to code-switches, which might contribute to phonetic cuing.

Experiment 3 tests whether Mandarin-English code-switching might incur an asymmetric switch cost due to differences in dominant language and frequency, by comparing looks to English-to-Mandarin switches and Mandarin-to-English switches in an eye tracking study. Mandarin-English bilingual listeners (N=48) of varying language dominance scores (Birdsong, Gertken & Amengual, 2012) participated in an eye tracking task in which they were auditorily presented Mandarin and English sentences with and without code-switched target words. Compared to unswitched targets, the average proportion of all participants' looks to target pictures corresponding to English code-switches was higher, but there were fewer looks to Mandarin code-switches. This suggests an asymmetric switch cost where English code-switches in Mandarin sentences are easy to process but Mandarin code-switches in English sentences are more difficult in terms of processing time. Mandarin-dominant bilinguals looked more toward targets corresponding to Mandarin words, suggesting a language dominance effect that is unexpected under influential models of code-switching.

These studies suggest that processing code-switches need not be costly: processing code-switched Mandarin words incurs a cost, which can be modulated by the presence of anticipatory phonetic cues depending on the speaker, but processing code-switched English words does not. Dominant language and the frequency of code-switch by language are influential factors in Mandarin-English bilingual auditory comprehension. Implications of these findings for models of code-switching and bilingual language control are discussed, along with possible mechanisms underlying the phonetics of code-switched speech.

To my mom.

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## Chapter 1. Introduction

Code-switching, or the alternation between two languages in the same stretch of discourse, is a common practice among many bilinguals, or speakers of two (or more) languages (Bullock & Toribio, 2009)\*. However, the majority of psycholinguistic research on code-switching has demonstrated a switch cost, or an increased processing cost – from 20 to more than 100 ms<sup>†</sup> – when faced with a language switch (e.g. Grainger & Beauvillain, 1987; Meuter & Allport, 1999; Thomas & Allport, 2000; Costa & Santesteban, 2004).

The idea of a switch cost seems counterintuitive given many bilinguals' reported experience of code-switching effortlessly and sometimes subconsciously. Additionally, recent research has found that code-switching is not necessarily costly. One reason that code-switching might not incur a switch cost in natural daily language use is the nature of switching during bilingual experiments, such as having switch trials that cue a particular language. For instance, Kleinman and Gollan (2016) found that switch costs were eliminated when bilinguals relied on lexical accessibility in semi-voluntary switching compared to when bilinguals were forced to switch. Moreover, experimental paradigms can be unnatural, such as single-word trials in a picture naming task, or carrier phrases that lack sentential context. In natural conversations in daily life, contextual information is available, whether phonetic, morphosyntactic, or semantic. If experimental paradigms create unnatural switching scenarios, then the resulting processing cost might not necessarily reflect how bilinguals manage code-switches in natural conversations in daily life.

A key issue with research on switch costs is the dearth of work on auditory comprehension despite the fact that most natural code-switching takes place in spoken conversation. While there are many studies concerned with spoken language production, or reading or visual word recognition, it is uncertain whether those results can be directly extrapolated over to auditory comprehension. One of the only known studies that actively investigates switch costs in auditory comprehension is Olson's (2017) study on Spanish-English bilinguals, which found 40-50 ms switch costs for the experimental block with single-word insertions in sentences, but no switch cost for the block with a greater proportion of switches, i.e., consistent alternational code-switching in sentences. This finding suggests that the assumption that code-switches necessarily incur a processing cost is unwarranted.

Indeed, a recent line of research on the auditory comprehension of code-switching in Spanish-English bilingual speech has shown that the unique contextual information that occurs along with producing bilingual speech can serve as cues for listeners to anticipate upcoming code-switches, even single-word insertions. Specifically, phonetic reflexes such as voice onset time (VOT) and prosody (Fricke, Kroll, & Dussias, 2016; Piccinini & Garellek, 2014) or syntactic patterns in grammatical gender and auxiliary-participle constructions (Valdes Kroff, 2012; Guzzardo Tamargo, Valdes Kroff, & Dussias, 2016) occur in predictable ways in code-switched utterances such that they can cue upcoming code-switches for Spanish-English

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\* These are quick working definitions of key terms, which I further discuss in the next section: Bilingualism and code-switching.

<sup>†</sup> Though such processing costs might seem so small as to be potentially imperceptible, and therefore without substantive real-world impact, monolingual listeners have been shown to be sensitive to 5 ms VOT differences (McMurray, Tanenhaus & Aslin, 2002), while a study showing that bilingual listeners are sensitive to anticipatory phonetic cues found that the speech rate of code-switched utterances were 16 ms slower than comparable unilingual utterances (Fricke, Dussias & Kroll, 2016).



bilinguals during auditory comprehension. For example, code-switching from a long-lag VOT language (e.g. English) to a short-lag VOT language (e.g. Spanish, French, Greek) results in the stops in the long-lag VOT language shortening (Goldrick, Runqvist, & Costa, 2014; Piccinini & Arvaniti, 2015; Antoniou, Best, Tyler, & Kroos, 2011; Balukas & Koops, 2015).

Moreover, the processing of code-switching might reflect bilinguals' code-switching experience and habits. Distributional patterns from code-switched speech can guide processing during auditory comprehension (e.g., Beatty-Martinez & Dussias, 2017). A study on the comprehension of Spanish-English code-switched auxiliary phrases demonstrated that speakers produce *estar* more frequently than *haber* with an English past participle and that this pattern was mirrored in listeners' processing costs (Guzzardo Tamargo et al., 2016). The frequency asymmetry seen in this example is likely to exist in other distributional patterns as well, and could result in corresponding processing asymmetries in auditory comprehension, such that one language is easier to process as a code-switch than the other. For example, if a bilingual often code-switches with Language A as the matrix language and Language B as the switch language, then they might experience an asymmetric switch cost.

Further experiential factors that could affect the processing of code-switches include age of acquisition, proficiency, residing in a monolingual vs. multilingual community, and restrictions posed by a bilingual's environment and available interlocutors. Since bilingual individuals' environments change, language processing, and therefore switch costs, may inherently be dynamic rather than static. In particular, these experiential factors tend not to be matched across a bilingual individual's two languages, which could result in a processing asymmetry due to one language being used or heard more often than the other. Broadly, studies on cognitive control have also shown that bilinguals who code-switch frequently perform better at task switching (Prior & Gollan, 2011; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2015); if constantly regulating use of the appropriate language strengthens bilinguals' non-linguistic switching reflexes, then it seems reasonable linguistic switching reflexes would be strengthened as well.

This dissertation explores switch costs in the auditory comprehension of code-switching between Mandarin and English, while taking into account whether anticipatory phonetic cues and bilingual individuals' experience with code-switching affect processing. The goals are to investigate: (a) whether switch costs are incurred, (b) if so, whether the specific kind of variability in the context preceding the code-switch might function as an anticipatory cue to mitigate or even eliminate the switch cost, and (c) whether asymmetries in bilinguals' experience of code-switching lead to asymmetric switch costs.

The bulk of code-switching studies focus on Indo-European languages, particularly Spanish and English. Studying Mandarin-English code-switching provides an opportunity to determine whether current findings in the field are generalizable to other languages. Moreover, the phonetic differences between Mandarin and English allow us to probe the variability and cue-functionality of yet unstudied phonetic reflexes of code-switching, such as tone. Moreover, different bilingual communities might have a different experience with code-switching. Mandarin-English bilinguals in the U.S. report asymmetries in code-switching, more often inserting English words into Mandarin sentences than Mandarin words into English sentences. If Mandarin-English bilinguals have more experience hearing and producing English code-switches in Mandarin sentences, then English code-switched words may have an advantage in recognition, thus resulting in an asymmetry in processing.

First, I investigate whether the auditory comprehension of code-switching incurs a switch cost, as well as the hypothesis that anticipatory phonetic cues may mitigate any switch cost. In Chapter 2, I discuss two experiments in which Mandarin-English bilingual participants were tasked with recognizing unilingual and code-switched target words in English sentences. In both experiments, stimuli were acoustically manipulated in one condition to effectively withhold anticipatory phonetic cues to the code-switch. The target words were spliced out of code-switched sentences into sentences that were originally recorded entirely in English. If bilingual listeners are sensitive to and rely on anticipatory phonetic cues to code-switches, then they will more quickly recognize code-switched target words that have not been spliced, i.e. retain their natural phonetic context, than those that have been spliced.

Experiment 1 is a concept monitoring experiment that simultaneously presents a visual stimulus along with an auditory sentence stimulus. Participants monitored for the object pictured in the visual stimulus and pressed a button when they recognized the spoken word corresponding to the pictured object. Their reaction times during trials with unilingual English target words were compared to those during trials with code-switched Mandarin target words to determine whether there is a switch cost. Reaction times during code-switched trials with unspliced target words were compared to those during trials with spliced target words to determine whether anticipatory phonetic cues mitigate switch cost.

Experiment 2 is an eye-tracking experiment that employs the visual world paradigm, presenting a grid of four pictured objects, one of which is named in the accompanying auditory sentence stimulus. Participants' eye movements were monitored as they recognized the picture corresponding to the target word. Real-time processing results from spliced code-switched trials and unspliced code-switched trials were compared to determine whether the withholding of anticipatory phonetic cues through splicing makes the recognition of a code-switched word more difficult.

Second, I investigate the role of bilingual experience on potential asymmetries in switch costs. In Chapter 3, I discuss Experiment 3, an eye-tracking study with both English and Mandarin sentence stimuli, in which I not only investigated phonetic cues, but also the potential roles of dominant language and frequency, as measures of how language use and experience can result in a processing asymmetry. Dominant language is operationalized as based on proficiency, history, exposure, use, identity, and attitudes, factors which are accounted for in the Bilingual Language Profile questionnaire used throughout this study (Birdsong, Gertken, & Amengual, 2012).

In Chapter 4, I discuss the takeaways from all three experiments in the broader context of phonetics and psycholinguistic research on code-switching. The idea of switch costs in auditory comprehension is considered in the context of cuing and bilingual experience, and predictions made by previous studies and models of code-switching. The phonetic reflexes of Mandarin-English code-switching and their potential as anticipatory phonetic cues to code-switching are discussed. Finally, limitations and future directions are outlined.

## **Bilingualism and code-switching: working definitions**

Several key concepts in this dissertation are at the center of ongoing debates in the field of bilingualism. Different researchers have defined these concepts in various ways. In this section, I lay out several perspectives on these ideas, and provide working definitions for the key terms that will be used throughout this dissertation, while contextualizing them within ongoing debates in the field.

### ***Who is considered bilingual?***

‘Bilingual’ is a term that is used frequently in research but that is difficult to operationalize. Typically, language research seems to have a distinct split between work on ‘bilingualism’ vs. ‘second language (L2) acquisition’, and therefore ‘bilinguals and ‘L2 learners.’ The term ‘bilingual’ is primarily used to refer to simultaneous bilinguals, who acquire two native languages at the same time. The term ‘L2 learners’ typically refers to late sequential bilinguals, who acquired a second language considerably later than the native language. Despite these usages, bilingualism can better be characterized on a continuum, or perhaps multiple dimensions, as most bilingual individuals cannot be so cleanly binned into one category or another due to variation. For instance, heritage speakers tend not to be dominant in their native language, but rather in the community language that was acquired later on. On the other end of the spectrum, when does a monolingual speaker who is in the process of acquiring a second language become a bilingual? Even individuals who might broadly be considered bilingual have inequivalent levels of proficiency in speaking, understanding, reading, and writing each of their languages. For instance, some heritage speakers who are similarly proficient in speaking and understanding both languages may not be as similarly proficient in reading and writing each of those languages. But disqualifying them from being characterized as bilingual would be arbitrary and prescriptivist, since that would disregard their language history, not to mention sociocultural aspects of bilingualism, such as identity in and attitudes toward each language and culture and community. Therefore, bilingualism must be understood as on a continuum, and the myth of ‘balanced bilinguals,’ or those equally proficient in both languages, must be eradicated. Instead, bilingualism and language dominance must account for variation in proficiency, history, identity, attitudes, and use. Since this dissertation focuses on spoken language comprehension, individuals who (a) are either simultaneous bilinguals, or heritage speakers of Mandarin, or L2 learners of English, (b) are proficient in speaking and understanding both languages, (c) actively use both languages, especially in code-switching, and (d) identify as Mandarin-English bilinguals were recruited to be the bilingual participants in this study.

### ***What is considered bilingual speech?***

Bilingual speakers can be characterized as having language modes, on a continuum ranging from monolingual language mode – the sole use of one language – to bilingual language mode – the active use of both languages (Grosjean, 2001). In between are intermediate language modes, such as interacting with a bilingual who will rarely or occasionally insert words from the second language, as opposed to a bilingual who is constantly alternating between both languages. In this framework, code-switching falls on the bilingual language mode side of the spectrum, with certain types of code-switching being more intermediate. For example, the following code-

switched utterance taken from a corpus of Singaporean Mandarin-English bilingual conversations would be closer to bilingual language mode, having a nearly equal amount of elements from each language: "...then 三个 那个 business business math 还有 science convert 到来 就是 八个 东西 对吧 I think 八个 module 想读" (Lyu, Tan, Chng, Li, 2015). This is an example of alternational code-switching, where there is a constant alternation between both languages (Muysken, 1997). Another code-switched utterance from that same corpus might be considered more of an intermediate language mode, with one English element in a primarily Mandarin question, also known as insertional code-switching: "你可以比较它的 price 吗?" (Lyu et al., 2015). Both of these examples are considered intra-sentential code-switching, where elements of both languages occur within a single sentence. Code-switching that occurs across sentence boundaries, such as when one sentence is produced in English but the next in Mandarin, is called inter-sentential code-switching (Muysken, 1995).

A helpful framework for understanding intra-sentential code-switching is Grosjean's (1988) base language framework, which characterizes insertional code-switching from the perspective of language processing: an element from  $L_a$ , the guest language, is inserted or embedded into  $L_b$ , the base language. Myers-Scotton's (1993) Matrix Language-Frame Model, captures the same phenomenon in the context of language contact phenomena, with the base language and guest language respectively called the Matrix Language (ML) and Embedded Language (EL). The embedded element can be a morpheme, word, or syntactic constituent.

The degree to which an embedded element is integrated on different linguistic levels into the matrix or base language determines whether it is considered to be a code-switch or a borrowing. According to Grosjean (1988), guest elements that are morphologically or phonologically integrated into the base language are "nonce borrowings" rather than code-switches. Nonce borrowings are similar to language borrowings or loanwords, in that both are lexical items adopted from another language and fully linguistically integrated, but nonce borrowings are only temporarily borrowed by an individual, whereas actual loanwords are adopted on a community level. Van Coetsem's (2000) framework defines loanwords as lexical items borrowed from a Source Language (SL) into a Recipient Language (RL). Loanwords are etymologically foreign to the RL lexicon, but after being integrated on phonological, morphological, and syntactic levels, they are generally indistinguishable from other RL lexical items, and their use has been conventionalized. In contrast to loanwords, intra-sentential code-switches and nonce borrowings are syntactically integrated into the base language, to obey grammatical constraints (Poplack, 1980). But while nonce borrowings are morphologically or phonologically integrated, code-switches are not.

The identity of the speaker is also important to identifying what is a code-switch: a monolingual speaker who has learned one word from a foreign language and inserts it into an utterance, morphophonologically integrated or not, cannot be said to be code-switching. Code-switching is only performed by bilingual individuals who are proficient in and actively speak and use both languages.

In this dissertation, the stimuli include English sentences with single-word Mandarin insertions and Mandarin sentences with single-word English insertions. These utterances are produced by two self-identifying Mandarin-English bilingual speakers who actively use and are proficient in speaking and understanding both languages, often in bilingual language mode with friends and family. The inserted words are not morphologically or phonologically integrated into the base language. Code-switches are not phonologically integrated into the base language but

their pronunciation can still be influenced by the base language, as a result of language co-activation (e.g., Flege & Port, 1981; Spivey & Marian, 1999; Marian & Spivey, 2003; Weber & Cutler, 2004; Simonet, 2014; Simonet & Amengual, 2020). This phenomenon is known as phonetic transfer (e.g. in Olson, 2016), and its occurrence during bilingual speech will be discussed in-depth in the following chapters as ‘code-switched pronunciation,’ or ‘phonetic reflexes of code-switching.’ I will return to discussing this phenomenon in Chapter 2.

## Chapter 2. Withholding anticipatory phonetic cues to Mandarin code-switches<sup>‡</sup>

### Introduction

Bilinguals frequently switch between languages mid-utterance. Many psycholinguistic studies on code-switching have reported a ‘switch cost’, i.e., an increased processing time, in production (Meuter & Allport, 1999; Thomas & Allport, 2000; Costa & Santesteban, 2004; Gollan & Ferreira, 2009, although see Kleinman & Gollan, 2016), recognition (Soares & Grosjean, 1984), and comprehension (Olson, 2017). How then do bilingual listeners manage the potentially difficult processing task of recognizing a code-switched word? A recent line of research points to subtle details of pronunciation as a possible key to this question.

For instance, Fricke, Kroll and Dussias (2016) report subtle shifts in VOT before an English-to-Spanish code-switch, while Piccinini and Garellek (2014) report subtle shifts in intonation prior to code-switches in either direction. They further found that bilingual listeners use shifts in VOT and intonation as cues to anticipate code-switches. Phonetic cues to upcoming code-switches (henceforth ‘code-switching pronunciation’) may thus mitigate switch cost.<sup>§</sup>

There are at least three possible mechanisms by which code-switching pronunciation might arise. One is a ‘blending’ mechanism at the phonological level, by which code-switching pronunciation might represent a blend of the prosodic features of both languages (Grosjean, 2012; Olson, 2013): The matrix language may come to sound more like the switch language, or vice versa. For example, Piccinini and Garellek (2014) observed that stressed syllable pitch patterns in Spanish/English code-switched contexts was intermediate between those observed in unilingual contexts in either language. If such ‘intermediate’ prosodic contours are characteristic of utterances containing code-switches, they could serve as cues to an upcoming code-switch.

Another possibility is a ‘preparation’ mechanism at the phonetic level, by which code-switching pronunciation might reflect articulatory gestures that are preparatory to the production of a specific code-switched target.

These two explanations are mutually compatible, but entail slightly different empirical predictions. Under blending, code-switching pronunciation would be independent of specific upcoming code-switched targets. Under preparation, by contrast, the acoustic consequences of speakers preparing code-switched targets would depend on the articulatory gestures needed to prepare a specific target. Of course, code-switched utterances might very well be characterized both by general code-switching pronunciation patterns, such as the prosodic contours found in Piccinini and Garellek (2014), as well as by context-specific pronunciations arising in preparation for a specific code-switching target.

A third possibility is that code-switching pronunciation might reflect global cognitive costs of code-switching: If code-switching incurs a processing cost for the speaker, that increased processing load might cause an overall slowed speaking rate. Under this scenario, the existence and degree of ‘code-switching pronunciation’ would depend on the degree of processing load

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<sup>‡</sup> This chapter was previously published as: Shen, A., Gahl, S., & Johnson, K. (2020). Didn't hear that coming: Effects of withholding phonetic cues to code-switching. *Bilingualism: Language and Cognition*, 1-12. doi:10.1017/S1366728919000877

<sup>§</sup> On the other hand, code-switching pronunciation could potentially make the comprehension process more difficult: perseverative coarticulation of matrix language phonetics into the code-switch – or indeed of the switch language back into the matrix language – might be detrimental to recognition.

(see e.g., Gollan, Kleinman & Wierenga, 2014, for evidence showing that code-switching does not necessarily or consistently entail a processing cost in production). We will not pursue this possibility further here, except to note that it is in principle compatible with both the blending and preparation scenarios: Code-switching pronunciation may be a variable phenomenon modulated by processing demands of a specific code-switching context.

Phonetic consequences of code-switching should also differ across language pairs. The literature on phonetic reflexes of code-switching has so far been limited to English-Spanish, English-French, and English-Greek code-switching. One goal of the current study is to widen the evidence-base on the possible role in comprehension of phonetic reflexes of code-switching, by examining English-Mandarin code-switches.

We hypothesized that the comprehension of code-switched targets would differ depending on whether code-switched targets were spliced into utterances that were originally unilingual vs. utterances that originally contained code-switches. If that is the case, it would strongly suggest that there must be phonetic differences between unilingual vs. code-switched utterances<sup>\*\*</sup>, that these differences are perceptible and used by listeners as cues to upcoming code-switches, and that listeners consequently become faster at recognizing those code-switched words. In other words, if it is true that bilingual speakers produce phonetic cues and listeners use them in comprehension, then manipulating the acoustic signal to remove those cues should impede recognition of the code-switch: If phonetic preparation acts as a ramp to ease the gradual transition to another language or to highlight the phonetic contrast between the languages, then removing the phonetic ‘ramp’ should make code-switches phonetically abrupt and difficult to anticipate.

While the current study was primarily designed to target the possible role of phonetic reflexes of code-switches on the comprehension process, we also analyzed the pitch contours of our stimuli, as a step towards pinpointing what acoustic events might be responsible for effects of the splicing manipulation on comprehension and to explore whether phonetic cues to code-switching were target-specific.

We focus on pitch contours because Mandarin has lexical tone while English does not. It is conceivable therefore that pitch patterns in English contexts preceding switches into Mandarin might reflect tonal properties of the Mandarin target. For example, pitch might dip in anticipation of a low tone, such that there is assimilatory anticipatory coarticulation with pitch ramping to meet the low onset of that low tone.

Tonal coarticulation has been observed in unilingual Mandarin speech (Xu, 1997), which we describe in detail in the Acoustic Analysis section later on. English-to-Mandarin code-switching pronunciation might result in patterns resembling patterns of unilingual Mandarin tonal coarticulation. Alternatively, English-to-Mandarin code-switching pronunciation might differ from unilingual Mandarin tonal coarticulation: English does not have lexical tone, so pitch contours can in principle vary more freely in English than in Mandarin.

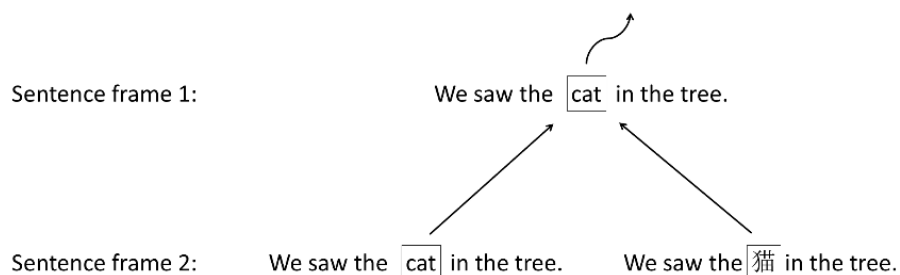
Tone-specific patterns are expected under the ‘preparation’ explanation for code-switching pronunciation, but not under the ‘blending’ explanation. The tonal coarticulation observed in Xu’s (1997) study differed based on which of the four lexical tones in Mandarin was being produced. Tone-specific patterns would thus be produced in preparation for a particular tone on an upcoming syllable, whereas ‘blending’ explanations would cover more general

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<sup>\*\*</sup> We can think of unilingual and code-switched utterances as two idealized ends of a continuum, with borrowings and single-word insertions somewhere in between.

phonetic patterns such as if a speaker produced a broader pitch range when code-switching between Mandarin and English. Exploring these patterns can aid us in understanding the potential role of anticipatory coarticulation in code-switching pronunciation.

To test the hypothesis that anticipatory phonetic cues aid in processing code-switches, we conducted a concept monitoring experiment and an eye tracking experiment. For both experiments, we spliced Mandarin code-switched target words from English-Mandarin code-switched sentences (e.g., *I saw a màozi*) into English sentences that were originally unilingual (e.g., *I saw a hat*) to withhold any anticipatory phonetic cues to the code-switch. The resulting spliced stimulus should bias the listener toward expecting the utterance to continue in English, as code-switch cues are absent. We compared listeners' reaction times and proportions of looks to English and Mandarin targets spliced into English utterances that originally did vs. did not contain Mandarin targets, as illustrated in Figure 1. This resulted in four conditions: code-switched spliced, code-switched unspliced, unilingual spliced, and unilingual unspliced.



**Figure 1.** Splicing auditory stimuli. The speaker recorded two sentence frames per experimental item: unilingual English sentences were recorded twice, and code-switched sentences were additionally recorded as unilingual English sentences. Target words were then cut from the unilingual or code-switched sentence frame and spliced into the fully English sentence frame.

Our prediction was that listeners will take longer to recognize code-switched target words, especially when spliced into unilingual utterances, since there would be no code-switching pronunciation to cue listeners to the upcoming code-switch.

### Experiment 1: concept monitoring

This experiment tests whether listeners are slower to recognize Mandarin target words in English sentences if anticipatory phonetic cues to the code-switch are absent from the acoustic signal. This is tested by comparing reaction times to spliced and unspliced stimuli, in a concept monitoring experiment where participants see a pictured object and press a button when they hear the object named in an auditorily presented sentence. Spliced code-switched stimuli consist of a Mandarin target word spliced into an originally unilingual English utterance, so that the pronunciation in the portion of the utterance leading up to the target word will incorrectly bias the listener toward expecting an English target word. Unspliced code-switched stimuli consist of an originally code-switched English sentence with a Mandarin target word, so that the code-switching pronunciation leading up to the code-switched target word will aid in recognition of the code-switch. The prediction is that listeners will be slower to recognize the target when the



phonetic information available is incongruent with the code-switch, so reaction times to spliced code-switched stimuli will be slower than to unspliced code-switched stimuli.

## *Method*

### *Speaker*

A 21-year-old female Mandarin-English bilingual produced all of the auditory stimuli. She self-reported balanced usage of both languages in home and school environments, having acquired Mandarin from birth and English around age four. The speaker completed a written language background questionnaire asking for speaking, listening, reading, and writing proficiency self-ratings in both languages. She rated herself as proficient in English and Mandarin on a scale of 0-6, with 0 being low and 6 being high, as shown in Table 1. The speaker read over the list of stimuli before recording, to check for grammaticality, and to ensure familiarity with the sentences to avoid hesitations during recording. The speaker was also administered the Bilingual Language Profile (Birdsong, Gertken & Amengual, 2012), on which she scored -23 on a scale from -218 (very Mandarin-dominant) to 218 (very English-dominant), suggesting that she is a relatively balanced bilingual, though slightly more dominant in Mandarin. In addition, she reported having a positive attitude toward code-switching, frequently code-switching with friends, and occasionally with family.

	English	Mandarin
Speaking	5	6
Understanding	6	6
Reading	5	6
Writing	5	4

**Table 1.** Speaker self-rated proficiency, on a scale of 0 (low) to 6 (high).

### *Participant screening*

Participants were screened for proficiency prior to the experiments with two tasks. First, they were administered the same written language background questionnaire as was given to the speaker. They then completed a familiarization task, to check vocabulary size and to ensure association of the appropriate Mandarin and English names with the pictured objects. Participants were presented all visual stimuli one by one on a computer screen, along with printed English and Mandarin names for the pictured objects. The positions of the English and Mandarin names (left or right underneath the picture) were randomized. The task was self-paced, and participants were given an index card to note down any English and Mandarin words they were unfamiliar with, or if the words were not ones that they would typically use to name the pictured object. If the participant was likely not proficient enough to complete the study according to their questionnaire responses (i.e., scoring below 3 on the 1 (low) – 4 (high) understanding and speaking proficiency scales on the language background questionnaire) or if their vocabulary was too limited based on the familiarization task, they were disqualified from participating. A substantial vocabulary in both English and Mandarin, as well as familiarity with specific names of pictured objects was desirable, as the study relied on participants' being able to associate pictures with their spoken names in both languages. Therefore, any participants who

marked more than ten words (of a total of 224) as unfamiliar or not their primary choice for describing the picture in either language (e.g., due to dialectal differences) was disqualified from participating. The entire screening process for each participant lasted approximately twenty minutes.

### *Participant language background*

A total of 42 Mandarin-English bilinguals (35 female, 7 male) with no reported speech or hearing defects qualified for participation in this study. All participants but one completed both this experiment and Experiment 2. The participants' linguistic backgrounds and, consequently, their language dominance, varied. Thirty-five participants were L1 Mandarin speakers, one participant was an L1 English speaker, while six participants were simultaneous bilinguals. Twenty-three participants reported also speaking other languages, and four participants reported both Mandarin and other Chinese languages as their L1s: Wu (Shanghainese), Yue (Cantonese), and Southern Min. The average age was 20.4 years ( $SD = 2.2$ ). While most participants were 18-24, one male participant was 31 years of age. The average age of arrival to the U.S. was 15 years ( $SD = 7$ ), although two participants first lived in Canada starting at ages four and eight, before moving to the U.S. at ages 12 and 18, respectively. Additionally, several participants grew up in Singapore, where English is an official language and most of the population code-switches frequently. Most participants moved from China to the U.S. for college, while two each moved from Malaysia and Singapore, and one each from Taiwan and Hong Kong. Four participants were born and raised in the U.S. All participants reported occasionally or regularly code-switching with friends or family. Three participants were left-handed.

We quantified participants' language dominance using the Bilingual Language Profile (Birdsong et al., 2012), a questionnaire that assesses language dominance. The participants' scores ranged from -159 to 96, averaging -31 ( $SD = 59$ ), meaning that most participants leaned Mandarin-dominant. Twenty-seven participants had negative scores, suggesting Mandarin dominance, while the other fifteen had positive scores, suggesting English dominance.

Table 2 provides participants' average age of acquisition of English and Mandarin, as well as their self-rated proficiency of each language on a scale of 0-6, where 0 means "not well at all" and 6 means "very well." Participants rated themselves as being almost equally proficient in speaking, understanding, reading, and writing both languages.

	English	Mandarin
Age of acquisition (years)	5.4 (2.7)	1.2 (0.6)
Speaking	5.12 (0.89)	5.6 (0.73)
Understanding	5.36 (0.76)	5.7 (0.6)
Reading	5.3 (0.82)	5.5 (1.1)
Writing	5 (1)	4.98 (1.55)

**Table 2.** Mean participant age of acquisition and self-rated proficiency. Standard deviations are in parentheses.

### *Visual stimuli*

Visual stimuli consisted of 80 pictures from the Rossion and Pourtois (2004) colored line drawing database, or other public domain colored line drawings that visually resembled the Rossion and Pourtois (2004) set. All pictures depicted common objects, and were modified to the

same dimensions. Of the 80 pictures, 64 were target experimental items, in that the pictured objects were mentioned in the corresponding auditory stimulus sentence. The other 16 pictures functioned as part of catch trials, where the pictured object was not mentioned in the corresponding auditory stimulus.

### *Auditory stimuli*

Auditory stimuli consisted of 144 spoken English sentences: (a) 64 sentences that mentioned the paired visual stimulus, (b) the spliced versions of those 64 sentences that mentioned the paired visual stimulus, and (c) 16 sentences that functioned as catch trials, thereby not mentioning the paired visual stimulus.

The target experimental items included the 64 spoken English sentences with either English target words (32 unilingual sentences) or Mandarin target words (32 code-switched sentences), recorded by the speaker in random order. Sentences were constructed so that each mentioned a picturable noun. Picturable nouns occurred sentence-medially in half of the sentences and sentence-finally in the other half. This gave a total of 16 English sentences with medial nouns, 16 English sentences with final nouns, 16 code-switched sentences with medial nouns, and 16 code-switched sentences with final nouns. Sentences were designed with similar syntactic structures to control for intonational patterns: either 1) a main clause beginning with a subject pronoun, followed by a transitive verb and direct object, ending with a prepositional phrase, or 2) a subject pronoun, main verb, and embedded clause. In the former case, medial targets occupied the direct object position, while final targets were located in the prepositional phrase. In the latter case, final targets were located in the embedded clause. Target words were introduced by either a definite article, indefinite article, or possessive pronoun. Spliced versions of these 64 sentences were also constructed, as described in the Splicing section.

Additionally, 16 sentences were not target trials but functioned as catch trials instead, in that none of the picturable nouns heard in the auditory stimuli matched the pictured objects on the screen. For instance, participants might hear “I saw a raccoon behind the plant,” while being presented a picture of a zebra. The inclusion of these catch trials was to ensure that target loci were not predictable from the similar syntactic structures of the stimulus sentences. The catch trials were split evenly among the four kinds of stimuli, regarding position of the picturable noun and whether there was a code-switch. The intention was to prevent participants possibly using syntactic or contextual predictability to respond whenever they expected to hear a noun, e.g., pushing a button when they heard the determiner preceding the target noun. These sentences can be found in Appendix A.

### *Splicing*

This study utilizes a splicing manipulation in both experiments to test the prediction that listeners will have relatively more difficulty recognizing a code-switch (manifesting as slower reaction time) if anticipatory phonetic cues to the code-switch are withheld. The speaker recorded multiple repetitions of each auditory stimulus sentence, including English-only versions of code-switched sentences to use as frames in the splicing condition.

To eliminate any phonetic information provided in the sentence leading up to the target word that could cue the language of the target word, stimuli were cross-spliced, so that a Mandarin target originally recorded in a code-switched sentence was spliced into what was originally a unilingual English sentence. To control for any effects of the splicing manipulation

itself, English sentence stimuli were recorded twice, and English targets were identity-spliced into a separate repetition of the same English sentence. This procedure is illustrated in Figure 1.

Since the spliced and unspliced versions of each sentence were identical content-wise and would sound identical aside from the splicing effect, two lists were created in each experiment to avoid participants hearing the same sentence both spliced and unspliced. In each list, half of the items were spliced. The concept monitoring experiment had 64 distinct target sentences, so that each list had 32 spliced items (along with the 16 catch trial sentences). Participants were randomly assigned to one of two lists at the start of each experiment, with an equal number of participants assigned to each list.

### *Procedure*

Data collection took place in a sound-attenuated booth in the PhonLab in the Department of Linguistics at the University of California Berkeley. Prior to the experiment, participants were presented with printed English instructions on a computer screen, informing them that they would hear a sentence while an image is displayed on the screen. Instructions stated that participants would hear both English and Mandarin throughout the experiment, and asked that they press a button if they heard the pictured object mentioned in the sentence. An experimenter was present to answer questions, as well as to clarify that: a) the pictured object would sometimes not be mentioned (i.e., in catch trials), and in that case, not to press a button, and b) participants were to press a button if the pictured object were named at all, in either language. Auditory stimuli were presented through headphones. During each trial, participants saw a picture in the center of the computer screen, and heard a spoken sentence that mentioned the pictured object. The task was to press a button as soon as they heard the object mentioned in the sentence. Presentation of trials was randomized, and a 1000 ms delay occurred between trials. Each trial lasted 3000 ms. The experiment lasted approximately fifteen minutes.

This experiment (concept monitoring) was counter-balanced with the next experiment (eye tracking); participants were randomly assigned the order in which to complete the two experiments. After completion of both experiments, participants were administered the Bilingual Language Profile (Birdsong et al., 2012) as well as a questionnaire asking about their code-switching attitudes and behaviors. The entire study lasted around 45 minutes, and participants were compensated \$5 for the completion of each of the three components, for a total of \$15.

Reaction times were measured as the latency between the onset of the target word and the subject's keypress response. Catch trials were first excluded from analysis, so that there were a total of 2688 target trials (64 unique stimuli x 42 participants). Data was then trimmed to remove trials with reaction times that were under 200 ms or longer than the trial duration. This resulted in the loss of 47 observations. Additionally, trials with target words that participants noted as unfamiliar during the familiarization task were excluded. Finally, each participant's mean was calculated, and any reaction times that were more than two standard deviations from that participant's mean were excluded from analysis. Only two observations were removed as outliers in this manner. After trimming, 2506 observations remained for analysis, so that approximately 7% of the target data was excluded.

### Data analysis

Since the data distribution was right-skewed, reaction times were log-transformed. The log-transformed data was then modeled with a linear mixed effects regression, shown in Table 3. The model considers an interaction between whether a target word is a code-switch or not (Switch), spliced or unspliced (Splice), and sentence-medial or sentence-final (Position), and includes random slopes for Splice-by-item and Switch-by-subject (Baayen, Davidson & Bates, 2008).

Random effects					
Groups	Name	Variance	Std. Dev.	Corr.	
Item	(Intercept)	0.012630	0.11238		
	Splice – Yes	0.008644	0.09298	-0.28	
Subject	(Intercept)	0.182096	0.42673		
	Switch – Yes	0.008807	0.09385	-0.40	
Residual		0.095446	0.30894		

Fixed effects					
	Estimate	Std. Error	df	t value	Pr(> t )
(Intercept)	6.56940	0.07348	59.09000	89.400	<2e-16 ***
Switch-Yes	0.09113	0.04766	79.03000	1.912	0.0595 .
Splice-Yes	0.04653	0.03367	58.68000	1.382	0.1722
Position-Medial	0.21737	0.04620	63.27000	4.705	1.42e-05 ***
SwitchY:SpliceY	-0.05988	0.05089	61.79000	-1.177	0.2438
SwitchY:PosMed	0.01130	0.06449	66.30000	0.175	0.8614
SpliceY:PosMed	-0.01835	0.04742	58.17000	-0.387	0.7002
SwitchY:SpliceY:PosMed	0.04015	0.07000	59.63000	0.574	0.5684

**Table 3.** Linear mixed effects regression of log-transformed reaction times from Experiment 1.

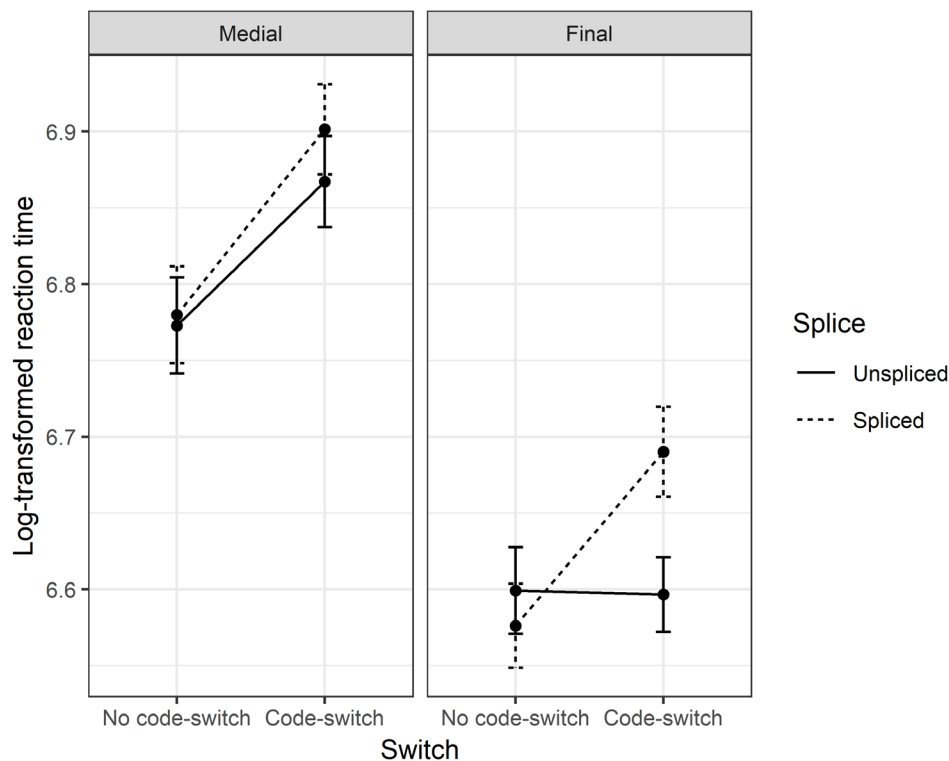
### Results

Table 4 shows average reaction time (in milliseconds) as a function of Switch, Splice, and Position. Generally, reaction times to code-switched targets were slower than to English targets (with the exception of final, unspliced targets), and reaction times to spliced targets were slower than to unspliced targets. However, the most noticeable difference is between reaction times to sentence-medial and sentence-final targets.

	No code-switch		Code-switch	
	Medial	Final	Medial	Final
Unspliced	1004 (549)	819 (410)	1097 (616)	798 (378)
Spliced	1033 (631)	826 (473)	1126 (611)	890 (474)

**Table 4.** Mean raw reaction times (ms), as a function of switch, splice, and position. Standard deviations are in parentheses.

The linear mixed effects regression model summarized in Table 3 and plotted in Figure 2 suggests that there was a significant effect of Position, and a tendency for Switch to affect reaction time. The target being code-switched is associated with longer reaction times ( $\beta = .091, t = 1.912, p = .059$ ). Reaction times to sentence-medial words were significantly longer than those to sentence-final words ( $\beta = .217, t = 4.705, p < .001$ ). However, Splice was not a significant effect ( $\beta = .047, t = 1.382, p = .173$ ). Additionally, the interaction between Switch and Splice is not significant, suggesting that reaction times for code-switched trials are not predicted to differ significantly depending on whether they were spliced or unspliced.



**Figure 2.** Log-transformed mean reaction times, by position, switch, and splicing conditions. Vertical lines represent standard errors.

We also fit a model that included participants' language dominance from the Bilingual Language Profile, since our participants' linguistic backgrounds varied. This model had an interaction between Switch, Splice, Position, and Dominance. While this model performed worse than the one in Table 3 as evaluated by both models' Akaike Information Criteria and log likelihoods, Switch was significant in this model ( $\beta = .013, t = 2.62, p = .01$ ), as was the interaction between Switch and Dominance ( $\beta = .0001, t = 2.52, p = .01$ ), and Switch, Position, and Dominance ( $\beta = .0001, t = -2.98, p = .003$ ). This suggests that participants with a more positive BLP score (i.e., more English-dominant participants) had slower reaction times to code-switches, especially sentence-medial code-switches.

Due to participants' different backgrounds in country of origin, age of arrival to the U.S., and age of acquisition of English, we performed further analyses with the original model to determine whether excluding the ten participants who were not born and raised in China (i.e., from Singapore, Malaysia, Taiwan, Hong Kong, or the U.S.) affected the results. This was not

the case; The pattern of the results was unchanged. Exclusion of the five simultaneous bilinguals, who were also not born and raised in China, but rather the U.S., Singapore, and Hong Kong, also did not affect results.

### ***Discussion***

The results of this experiment are consistent with the switch cost finding in previous studies: Listeners were 20-100 ms slower to recognize code-switched words compared to words in a unilingual utterance. However, the absence of anticipatory phonetic cues did not have an apparent effect on the recognition of the code-switch, contrary to our initial hypothesis.

Assuming the intended anticipatory phonetic cues are present in the speech signal, this result suggests that perhaps Mandarin-English bilingual listeners did not detect or use such cues. However, while the reaction time measure used in this experiment revealed that Mandarin-English bilinguals are slower overall to recognize code-switches, it is possible that phonetic cues did affect the recognition process prior to and at the beginning of the code-switch, but that these effect had already dissipated before the button-press in the concept monitoring task.

The position of the target word had an interesting influence on recognition of code-switches. Though target word position was originally varied to prevent participants from predicting its location in the sentence by using syntactic cues like determiners and possessive pronouns, listeners took longer to recognize sentence-medial targets compared to sentence-final targets, regardless of whether the target was a code-switch or not. This difference could potentially be attributed to the reduction of uncertainty as the sentence progresses. After participants experience several trials, it might become clear that targets only occur medially, finally, or not at all, especially because sentences are controlled for syntactic structure. If participants are strategically expecting targets by syntactic position, rather than monitoring for the concept, then sentence-final targets might be easier. For example, if the participant has already heard the main clause but not the target, then the target is either sentence-final or will not occur.

Alternatively, listeners' use of phonetic information in sentence processing could be affected by the amount of time they have to incorporate such information; All sentence stimuli were similar lengths so that trials with sentence-final targets are preceded by a longer utterance than trials with sentence-medial targets. Future work can manipulate sentence length, word position, and number of catch trials to investigate the difference between medial and final targets.

The model including Dominance suggests that dominant language is a factor in code-switched recognition. English-dominant bilinguals were slower to respond to code-switched, i.e., Mandarin, targets. One interpretation is that switching out of one's dominant language and into the non-dominant language is more cognitively demanding. This pattern is reminiscent of the Inhibitory Control Model (Green, 1998), and what Olson (2017) found in comprehension, though with a different effect of dominant language: Instead of switching back into the dominant language being more costly due to the dominant language requires stronger inhibition, our bilinguals took longer to switch into their non-dominant language.

## Experiment 2: eye tracking

Experiment 1 showed that Mandarin-English bilinguals are slower to recognize code-switched words, but failed to show an effect of the absence of anticipatory phonetic cues on concept monitoring times. While an offline task like the concept monitoring experiment can reveal whether code-switched recognition incurs a switch cost, it may not give insight into the time course of recognition and whether and when phonetic cues are incorporated.

Online tasks such as eye tracking are advantageous for understanding the time course of lexical activation during spoken language comprehension (Cooper, 1974; Tanenhaus, Spivey-Knowlton, Eberhard & Sedivy, 1995). The visual world paradigm in eye tracking is a particularly good method for studying spoken word recognition (Allopenna, Magnuson & Tanenhaus, 1998; Altmann & Kamide, 2009; Huettig, Rommers & Meyer, 2011).

The visual world paradigm involves a visual display of pictures, with a simultaneous auditory stimulus naming one of the pictures. The pictures represent the target word and various lexical competitors, with participants' eye movements revealing when certain lexical items are activated during spoken word recognition. The auditory stimulus can be manipulated to test the role of different phonetic details in the process of recognizing a spoken word.

Experiment 2 uses the visual world eye tracking paradigm and splicing to investigate whether withholding anticipatory phonetic cues affects code-switched recognition. The visual world involves a display of four pictures, each corresponding to a different type of lexical candidate, and a simultaneous auditory stimulus so that the time course of lexical access is elucidated by the participant's fixations to pictures during perception of that continuous speech. The goal of this experiment is to probe which lexical candidates are considered during the processing of a code-switch, and whether bilingual listeners use phonetic information to constrain recognition to candidates in the expected language.

We predict that recognition of a code-switch will be hindered by a lack of phonetic cues to that switch. Therefore, in the spliced code-switched condition, we predict that listeners will fixate less on the target as compared to the unspliced code-switched condition, because the phonetic context will lack switch cues and bias them away from Mandarin. Listeners might therefore look at an English competitor early on, expecting a target in the same language as the sentence frame. In the unspliced code-switched condition, listeners will fixate more on the target, since available phonetic cues will bias them toward expecting a Mandarin code-switch. Listeners might also look toward the Mandarin competitor more than in any other condition, since only the unspliced code-switched condition involves phonetic cues signaling an upcoming Mandarin word.

### ***Method***

#### *Speaker and participants*

The speaker who recorded the auditory stimuli for Experiment 1 also recorded the auditory stimuli for this experiment.

Of the 42 participants who completed Experiment 1, data from one participant was excluded in Experiment 2 due to their corrective lens interfering with the eye tracker's calibration process.

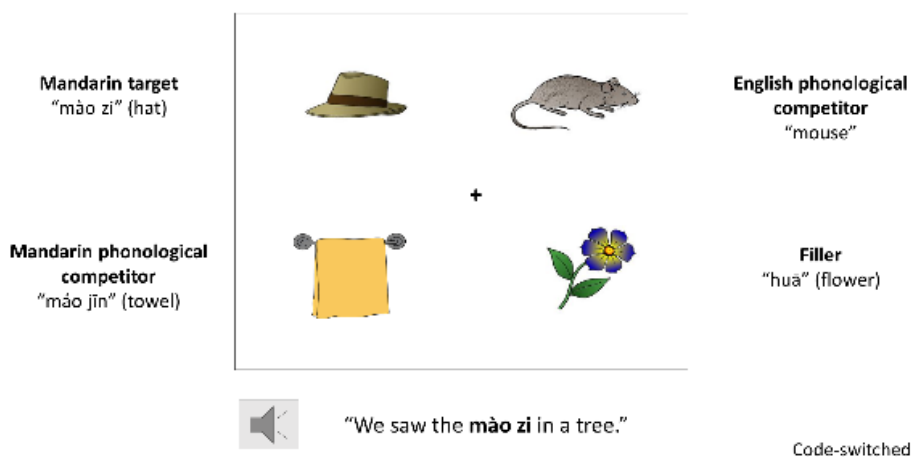


### Visual stimuli

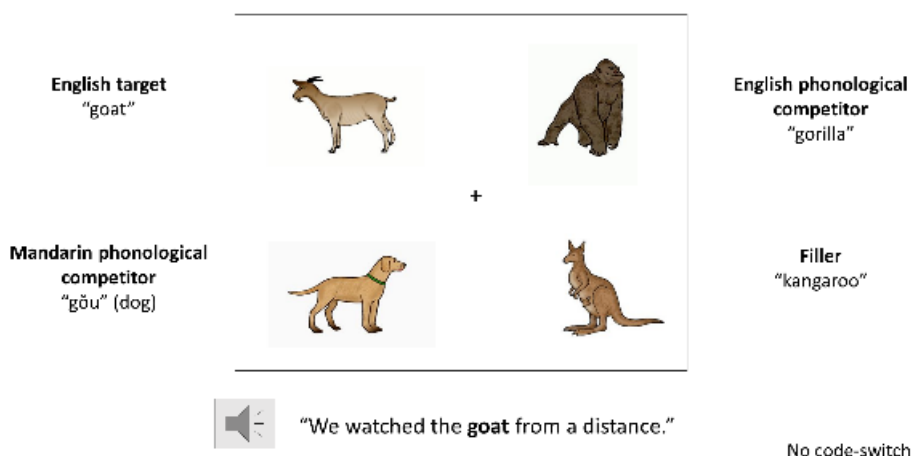
36 picturable nouns (18 Mandarin nouns, 18 English nouns) that have both picturable Mandarin and English noun cohort competitors were selected, for 18 sets of three picturable nouns. To each set, a distractor that was not a cohort competitor, i.e., did not share an onset, was added. This resulted in 36 sets of four picturable nouns. Colored line drawings in the Rossion and Pourtois (2004) database or available in public domain were selected for the picturable nouns.

### Auditory stimuli

A sentence was constructed for each set of four picturable nouns, resulting in 36 total sentences. The target noun was located sentence-medially in 18 sentences, and sentence-finally in the other 18 sentences. The portions of these sentences preceding the target were constructed so that any of the four picturable nouns in the set were semantically congruous with the verb. For example, a code-switched trial might have visual stimuli where the Mandarin target *màozi* [mao<sup>51</sup>tsi] corresponds to a picture of a hat, the cohort competitors in English and Mandarin, *mouse* [maos] and *máojīn* [mao<sup>51</sup>tɛin<sup>55</sup>], respectively correspond to pictures of a mouse and a towel, and the distractor corresponds to a picture of flower (*huā* [xwa<sup>55</sup>] in Mandarin). The corresponding auditory stimulus is the sentence *We saw the màozi in a tree* where any of the four picturable nouns in the set are semantically congruous as direct objects of the verb *saw*. Figure 3 and Figure 4 show example sets of visual world stimuli with a corresponding auditory sentence (where the target is sentence-medial) for both the code-switch and no code-switch conditions.



**Figure 3.** Example of visual world display in code-switched trial in Experiment 2.



**Figure 4.** Example of visual world display in unilingual (no code-switch) trial in Experiment 2.

Stimuli were spliced as in Experiment 1, so that a spliced version of each sentence was created. There was thus a total of 72 auditory stimuli: the spliced and unspliced version of nine unilingual stimuli with sentence-medial targets, nine unilingual stimuli with sentence-final targets, nine bilingual stimuli with sentence-medial targets, and nine bilingual stimuli with sentence-final targets. Participants only heard one version of each sentence, depending on their experimental list, given that spliced and unspliced versions of a sentence were identical aside from the phonetic manipulation. The sets of picturable nouns and their corresponding sentences can be found respectively in Appendix B and Appendix C.

### *Procedure*

Participants were seated a comfortable distance from the computer screen and an eye tracker (The Eye Tribe), which was then calibrated with a nine-point calibration. Sampling frequency of the gaze location was 60 Hz. Participants wore headphones for presentation of auditory stimuli. Text instructions displayed on the computer screen prior to the experiment informed participants that they would see images while hearing English and Mandarin throughout the experiment.

During each trial, participants saw a visual world display of four colored line drawings corresponding to four picturable nouns (target, English cohort competitor, Mandarin cohort competitor, and distractor). One picture was centered in each of the four quadrants of the screen. Then after a delay averaging 250 ms, participants heard a spoken sentence. Their task was to press a button as soon as they heard any pictured object in the display be named in the sentence. Each trial lasted 4000 ms. The positions of the four types of pictured objects in the visual world display were randomized across the four fixed quadrant positions for each trial, so that the same type of picture (e.g., target) was not always presented in the same quadrant.

The presentation of trials was randomized, and a 1000 ms delay occurred between trials with a central fixation cross. The eye tracking task lasted approximately ten minutes.

## *Data analysis*

Trials with a visual display including a picture corresponding to a noun that the participant marked as unfamiliar during the screening were excluded.

Looks to the quadrant of each type of picture in the visual world display (Mandarin or English target, English cohort competitor, Mandarin cohort competitor, distractor) were counted as fixations to that picture. To calculate the average proportion of fixations for a condition, the number of fixations toward a type of picture were summed across all trials in that condition and all participants, and then divided by the total number of trials in that condition.

The following analyses focus on the time window corresponding to increasing activation: from target word onset to 1200 ms, which is when target fixations plateaued. Following Mirman (2014), growth curve analysis with orthogonal polynomials was used to model the time course of fixations to the pictures corresponding to the target word and competitors.

Growth curve analysis is well-suited for analysis of eye tracking data, in that time is treated as a continuous variable. The addition of orthogonal polynomials allows modeling the shape of the time course of fixations. Upon visual inspection of the time course data, cubic orthogonal polynomials were chosen as the best approximation of the shape of the curve for proportion of looks over time. The random effects structure for each model included by-participant random slopes for Switch (Baayen et al., 2008).

To assess the best-fitting models for the data, a likelihood ratio test implemented with the `R anova()` function was used, starting with a baseline model. Variables were added gradually to produce several models varying in complexity, and ANOVA was used to compare the baseline model and these models. Log likelihood and Akaike information criterion (AIC) were then used to assess the best-fitting models for the data. The interactions between linear, quadratic, and cubic orthogonal polynomials with all fixed and random variables were included.

## ***Results***

### *Looks to target*

The model for looks to the target included the fixed effects of Position (whether the target occurred sentence-medially or -finally), Switch (whether the target was a code-switch), and Splice (whether the target was spliced). It treated sentence-final, no code-switch, and unspliced as the reference points, and statistical significance was calculated using the normal approximation. The model is shown in Table 5, and plotted in Figure 5.

	$\beta$	Std. Error	$t$ value	Pr(>  $t$  )
(Intercept)	0.6278	0.0163	38.4257	0.000e+00
Linear polynomial	0.5988	0.0513	11.6724	0.000e+00
Quadratic polynomial	-0.1980	0.0417	-4.7446	2.089e-06
Cubic polynomial	-0.1519	0.04	-3.7988	1.4541e-04
Position - Medial	-0.1849	0.0172	-10.7419	0.000e+00
Switch - Yes	-0.0769	0.0201	-3.8325	1.269e-04
Spliced - Yes	-0.0833	0.0159	-5.234	1.656e-07
Lin:PosMed	0.0278	0.0595	0.4665	6.408e-01
Quad:PosMed	0.1706	0.0593	2.8791	3.987e-03
Cub:PosMed	0.0653	0.059	1.1071	2.683e-01
Lin:SwitchY	0.0235	0.0691	0.3395	7.342e-01
Quad:SwitchY	-0.0257	0.0681	-0.378	7.055e-01
Cub:SwitchY	-0.0150	0.0672	-0.2236	8.230e-01
PosMed:SwitchY	0.1023	0.0298	3.4382	5.857e-04
Lin:SpliceY	-0.1066	0.0552	-1.9309	5.35e-02
Quad:SpliceY	0.0933	0.0552	1.69	9.106e-02
Cub:SpliceY	0.0613	0.0552	1.1202	2.626e-01
PosMed:SpliceY	0.1395	0.0253	5.5178	3.432e-08
SwitchY:SpliceY	0.0489	0.0296	1.6512	9.87e-02
Lin:PosMed:SwitchY	0.1047	0.1022	1.0243	3.057e-01
Quad:PosMed:SwitchY	0.186	0.1	1.859	6.305e-02
Cub:PosMed:SwitchY	-0.1029	0.098	-1.0494	2.94e-01
Lin:PosMed:SpliceY	0.1156	430.0873	1.325	1.852e-01
Quad:PosMed:SpliceY	-0.0675	0.0864	-0.781	4.348e-01
Cub:PosMed:SpliceY	-0.155	0.0856	-1.8118	7e-02
Lin:SwitchY:SpliceY	0.1868	0.1015	1.839	6.582e-02
Quad:SwitchY:SpliceY	0.053	0.0986	0.5377	5.908e-01
Cub:SwitchY:SpliceY	-0.0594	0.0959	-0.62	5.354e-01
PosMed:SwitchY:SpliceY	-0.1328	0.0438	-3.0324	2.426e-03
Lin:PosMed:SwitchY:SpliceY	-0.1751	0.1498	-1.1688	2.424e-01
Quad:PosMed:SwitchY:SpliceY	-0.1215	0.1449	-0.8387	4.016e-01
Cub:PosMed:SwitchY:SpliceY	0.0854	0.1402	0.609	5.42e-01

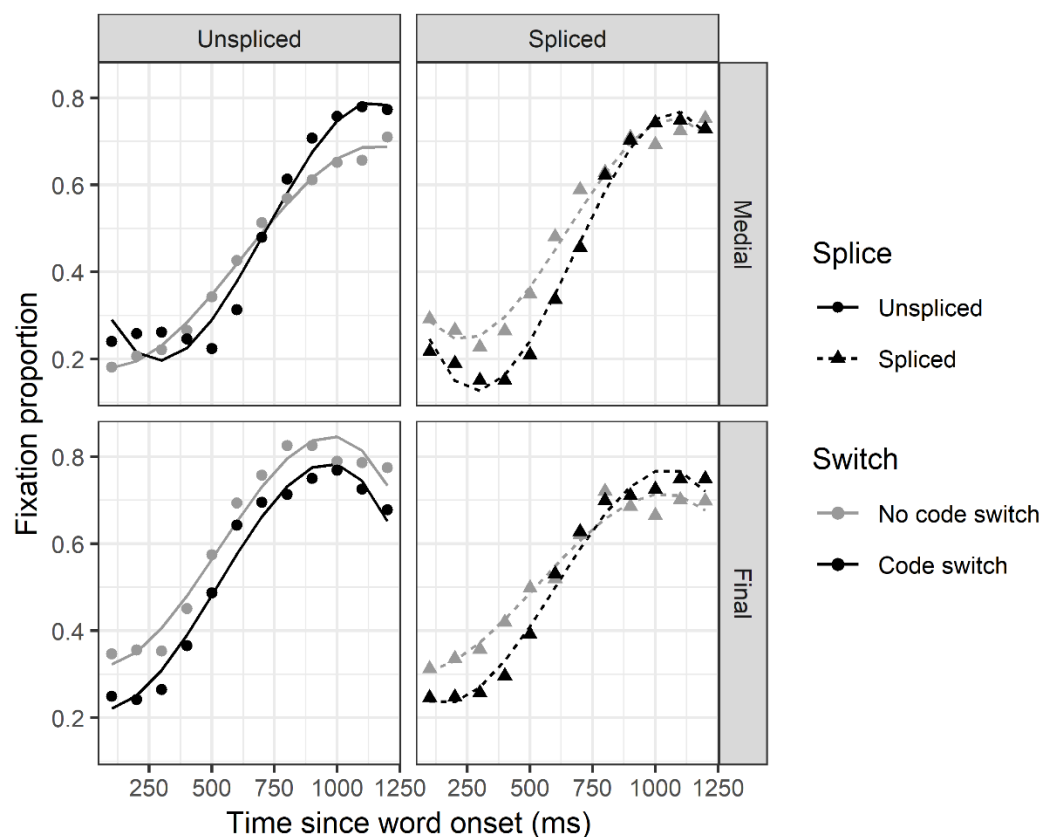
Groups	Name	Variance	Std.Dev.	Corr.
Subject	(Intercept)	0.005741	0.07577	
	ot1	0.045437	0.21316	0.60
	ot2	0.008961	0.09466	-0.14 0.15
	ot3	0.003069	0.05540	-0.77 -0.97 -0.12
Residual		0.062447	0.24989	

**Table 5.** Fixed and random effects of growth curve analysis of Experiment 2 eye-tracking data: Looks to the target, as a function of Position, Switch, and Splice.

All three fixed effects were significant in this model. The main effect of Switch was significant; there were fewer looks to code-switched than not switched targets ( $\beta = -.0769, t = -3.8, p < .001$ ). For example, participants would look toward the image of the tiger less often if they heard “She saw a picture of the *lǎohǔ*” than if they heard “She saw a picture of the *tiger*.” Position was also significant; there were fewer looks to sentence-medial than sentence-final targets ( $\beta = -.1849, t = -10.74, p < .001$ ). Finally, Splice was significant: there were fewer looks to spliced than unspliced targets ( $\beta = -.0834, t = -5.23, p < .001$ ).

The only interaction with an orthogonal polynomial to be significant was that between the quadratic term and Position. Although there were initially fewer looks to a sentence-medial target, the rate of looks to that target increased faster compared to a sentence-final target ( $\beta = .1706, t = 2.88, p = .004$ ).

The interaction between Position and Switch was significant. Participants looked at a medial target more when it was code-switched than when it was not code-switched ( $\beta = .1023, t = 3.44, p < .001$ ). The significant interaction between Position and Splice indicates more looks to a medial target when it was spliced than when unspliced ( $\beta = .1396, t = 5.52, p < .001$ ). Finally, the three-way interaction was significant; there were fewer looks to a sentence-medial code-switched target when it was spliced than when unspliced ( $\beta = -.1328, t = -3.03, p = .002$ ). For instance, presented with a code-switched utterance “We saw the *màozi* in a tree,” listeners looked toward the target image of the hat less if it was spliced into that frame.



**Figure 5.** Empirical data (points) and model fit (lines) for looks to the target picture, across all participants and trials.

Since participants differed in country of origin, age of arrival to the U.S., and age of acquisition of English, further analyses were performed to check whether participants could appropriately be analyzed as a single group. Excluding the nine participants who were not born and raised in China (i.e., from Singapore, Malaysia, Taiwan, Hong Kong, or the U.S.) from this analysis did not affect results. Exclusion of the five simultaneous bilinguals, a group which overlapped heavily with those born and raised outside of China, also did not affect results. Examination of individual results did not reveal any pattern among simultaneous bilinguals.

To account for differences in participants' backgrounds as in Experiment 1, we added participants' dominance scores from the BLP questionnaire as a continuous covariate in the model, such that we had an interaction between the orthogonal polynomials, Position, Switch, Splice, and Dominance. This model did not perform as well as the one shown in Table 5, as evaluated by their Akaike information criteria (AIC) and Bayesian information criteria (BIC) in a likelihood ratio test comparing it to the original model. Significance did not change for any of the original effects, but there was an additional significant interaction between Switch and Dominance: if the target was a final, unspliced code-switch, participants with more positive dominance scores (English-dominant) looked at the target less compared to if it were unswitched ( $\beta = -.001$ ,  $t = -2.95$ ,  $p = .003$ ). There was also a significant interaction between the linear orthogonal polynomial, Switch, and Dominance, such that the rate of fixations to final, unspliced code-switched targets increased faster for more English-dominant bilinguals than for more Mandarin-dominant bilinguals ( $\beta = .002$ ,  $t = 2.262$ ,  $p = .02$ ).

*Looks to the Mandarin competitor*

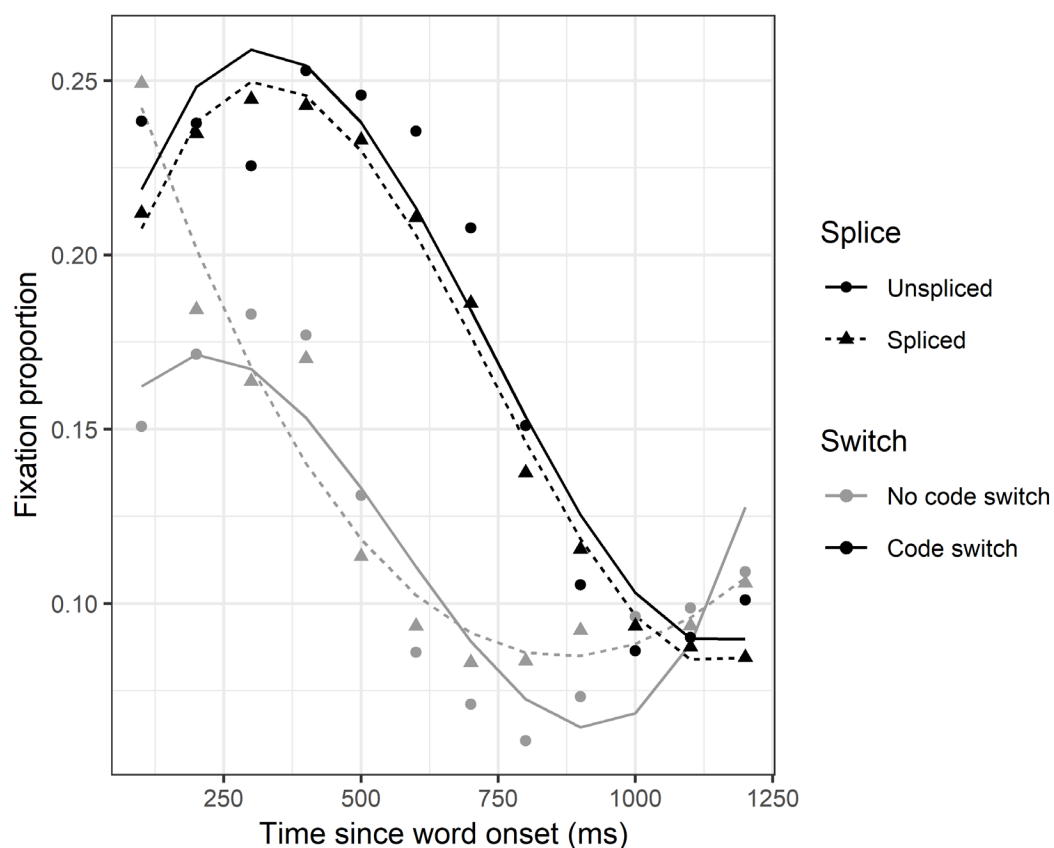
Looks to the Mandarin competitor were modeled with cubic orthogonal polynomials, fixed effects of Switch and Splice (baseline: no code-switch, unspliced), and by-participant random slopes. The model can be found in Table 6, and plotted in Figure 6.

	$\beta$	Std. Error	$t$ value	Pr(>  $t$  )		
(Intercept)	0.1174	0.0114	10.2814	0.000e+00		
Linear polynomial	-0.0999	0.0335	-2.9813	2.87e-03		
Quadratic polynomial	0.0572	0.024	2.3734	1.763e-02		
Cubic polynomial	0.064	0.0208	3.0807	2.065e-03		
Switch - Yes	0.0641	0.0118	5.4377	5.397e-08		
Splice - Yes	0.0153	0.0134	1.1466	2.516e-01		
Lin:SwitchY	-0.1035	0.0375	-2.7623	5.739e-03		
Quad:SwitchY	-0.1114	0.032	-3.4758	5.094e-04		
Cub:SwitchY	-0.0011	0.03	-0.03778	9.699e-01		
Lin:SpliceY	-0.0443	0.0407	-1.087	2.772e-01		
Quad:SpliceY	0.0447	0.031	1.4412	1.495e-01		
Cub:SpliceY	-0.0697	0.0279	-2.4986	1.247e-02		
SwitchY:SpliceY	-0.0232	0.0117	-1.9787	4.784e-02		
Lin:SwitchY:SpliceY	0.0498	0.0406	1.2253	2.205e-01		
Quad:SwitchY:SpliceY	-0.0455	0.0404	-1.1247	2.607e-01		
Cub:SwitchY:SpliceY	0.0706	0.0403	1.7507	8e-02		

Groups	Name	Variance	Std.Dev.	Corr.		
Subject:Language	(Intercept)	0.001462	0.038233			
	ot1	0.01218	0.110367	-0.31		
	ot2	0.004572	0.067616	0.28	-0.02	
	ot3	0.002159	0.04646	0.32	-0.08	-0.81
Subject:Splice	(Intercept)	0.002585	0.050843			
	ot1	0.02116	0.145457	-0.12		
	ot2	0.00711	0.084324	0.31	-0.37	
	ot3	0.003553	0.059605	0.42	-0.33	-0.54
Subject	(Intercept)	0.0004436	0.021062			
	ot1	0.0004436	0.021062	1.00		
	ot2	0.00009529	0.009762	-1.00	-1.00	
	ot3	0.0001252	0.01119	-1.00	-1.00	1.00
Residual		0.02093	0.144660			

**Table 6.** Fixed and random effects of growth curve analysis of Experiment 2 eye-tracking data: Looks to the Mandarin competitor, as a function of Switch and Splice.



**Figure 6.** Empirical data (points) and model fit (lines) for looks to the Mandarin competitor, across all participants and trials.

There was a main effect of Switch, showing that there were more looks to the Mandarin competitor in code-switched than in English unspliced trials ( $\beta = .0641, t = 5.44, p < .001$ ). Interactions between Switch and both the linear and quadratic terms were significant. The decay in looks to the Mandarin competitor was steeper in code-switched than in English unspliced trials ( $\beta = -.1035, t = -2.76, p = .006$ ;  $\beta = -.1114, t = -3.48, p < .001$ ). There was no main effect of Splice, although the interaction between the cubic term and Splice is significant ( $\beta = -.0697, t = -2.5, p = .01$ ). Therefore, the shape of the function capturing fixations to the Mandarin competitor differed in spliced versus unspliced trials without switches, although there was no difference between those conditions in proportion of fixations. Finally, the interaction between Switch and Splice was significant ( $\beta = -.0232, t = -1.98, p = .048$ ). There were fewer looks to the Mandarin competitor in code-switched trials when the target was spliced, compared to when the target was unspliced. For instance, if *màozi* was spliced into “We saw the *màozi* in a tree,” listeners looked toward Mandarin competitor *máojīn* less, than if *màozi* were not spliced.



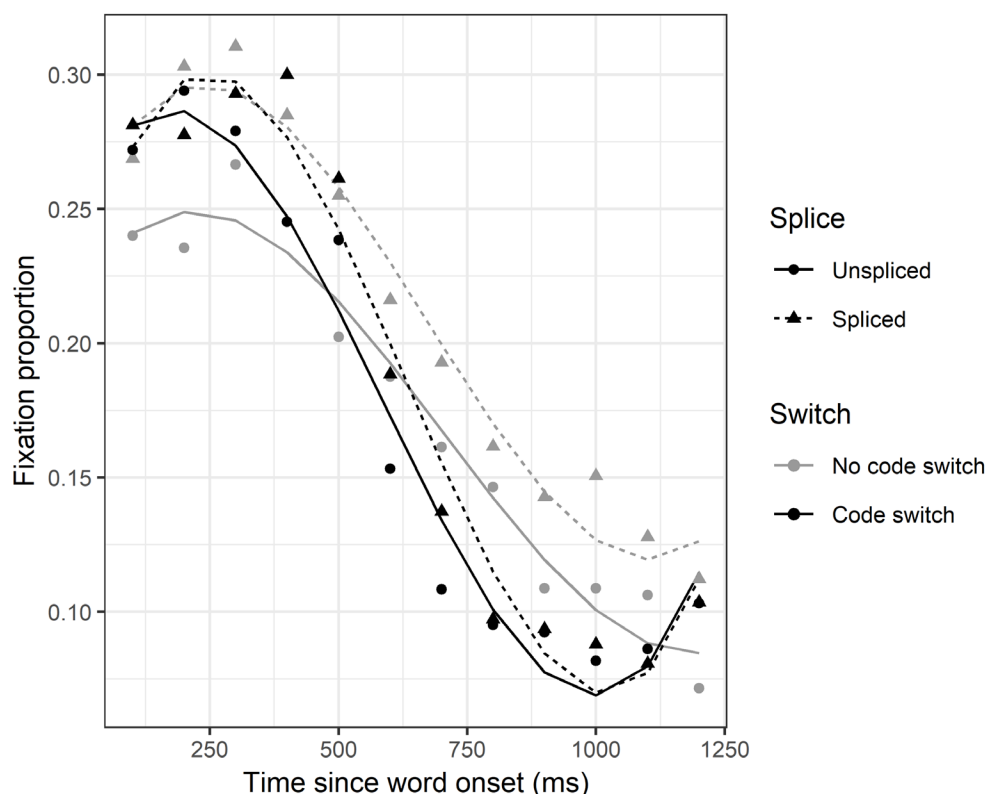
*Looks to the English competitor*

Looks to the English competitor were modeled in the same way as looks to the Mandarin competitor were, with cubic orthogonal polynomials, Switch, Splice, and by-participant random slopes. This model can be found in Table 7, and plotted in Figure 7, with model fits as lines and empirical data as points.

	$\beta$	Std. Error	$t$ value	Pr(>  $t$  )
(Intercept)	0.1698	0.0158	10.6795	0.000e+00
Linear	-0.2088	0.0427	-4.8909	1.003e-06
Quadratic	-0.0177	0.0283	-0.6253	5.317e-01
Cubic	0.0388	0.0255	1.5192	1.286e-01
Switch - Yes	0.0009	0.0173	0.0551	9.560e-01
Splice - Yes	0.0354	0.0181	1.9494	5.123e-02
Lin:SwitchY	-0.0565	0.0497	-1.1358	2.56e-01
Quad:SwitchY	0.0717	0.04263	1.6819	9.257e-02
Cub:SwitchY	0.0455	0.0392	1.1601	2.459e-01
Lin:SpliceY	-0.0169	0.0519	-0.3257	7.446e-01
Quad:SpliceY	0.0076	0.0359	0.2119	8.321e-01
Cub:SpliceY	0.0198	0.0354	0.5586	5.763e-01
SwitchY:SpliceY	-0.0227	0.0158	-1.4351	1.512e-01
Lin:SwitchY:SpliceY	0.0005	0.0547	0.0102	9.918e-01
Quad:SwitchY:SpliceY	-0.0433	0.0544	-0.7954	4.263e-01
Cub:SwitchY:SpliceY	0.0026	0.0542	0.0483	9.614e-01

Groups	Name	Variance	Std.Dev.	Corr.		
Subject:Language	(Intercept)	0.003678	0.06064			
	ot1	0.02057	0.1434	-0.42		
	ot2	0.007443	0.08628	-0.28	-0.18	
	ot3	0.001831	0.04279	0.50	-0.79	-0.46
Subject:Splice	(Intercept)	0.004815	0.06939			
	ot1	0.032	0.1789	0.02		
	ot2	0.003764	0.06135	-0.56	-0.50	
	ot3	0.003491	0.05909	-0.24	-0.95	0.44
Subject	(Intercept)	0.00000255	0.001597			
	ot1	0.0000009466	0.0009729	1.00		
	ot2	0.000008021	0.002832	1.00	1.00	
	ot3	0.000000005020	0.00007085	1.00	1.00	1.00
Residual		0.03809	0.1952			

**Table 7.** Fixed and random effects of growth curve analysis of Experiment 2 eye-tracking data: Looks to the English competitor, as a function of Switch and Splice.



**Figure 7.** Empirical data (points) and model fit (lines) for looks to the English competitor, across all participants and trials.

The near-significant effect of Splice suggests an increase in looks to the English competitor when the target word was spliced and unswitched ( $\beta = .0355$ ,  $t = 1.95$ ,  $p = .0512$ ), but all of the main effects failed to reach significance.

### **Discussion**

We found that withholding anticipatory phonetic cues affects code-switched recognition. These results suggest that removing anticipatory phonetic cues to a Mandarin code-switch in an English utterance can affect the processing of that code-switch. However, this effect is mediated by the position of the code-switch. Specifically, our study indicated fewer looks toward a spliced code-switched target in the sentence-medial condition than an unspliced code-switched target in the same condition.

This is consistent with what studies of Spanish-English bilingual listeners have found: that bilinguals can use phonetic cues (intonation and VOT) to anticipate an upcoming code-switch (Piccinini & Garellek, 2014; Fricke et al., 2016). In conjunction with these previous findings, our results suggest that while the presence of anticipatory switch cues is facilitatory, the absence of such cues can hinder code-switched recognition.

When anticipatory phonetic cues were withheld, there were fewer looks to a medial code-switch (compared to when cues were present), and also fewer looks to the Mandarin competitor during the switch condition. This suggests that cues point the listener to the switch language. Moreover, without anticipatory cues, listeners were more likely to look toward an English

competitor overall; with a lack of cues to another language, listeners expect English, the matrix language.

Our findings hinge on the position of the target word, as there is no interaction between Switch and Splice for sentence-final code-switched targets. Word position appears to play an important role in recognition, whether code-switched or not, since all sentence-final targets received more looks than sentence-medial targets. As mentioned in the discussion of Experiment 1, this effect could be due to context, processing time, and various other factors.

Moreover, it appears that participants' different language backgrounds, including age of arrival to the U.S., age of acquisition of English, and country of origin (which might affect the variety of Mandarin spoken), did not affect results. The alternate model that includes dominance does suggest that while bilinguals who were more English-dominant looked at the target less when it was a code-switch, the role of anticipatory cues in recognition was not affected by language dominance. Perhaps sensitivity to phonetic cues is unaffected by a perceiver's dominant language, but processing those cues is more difficult when switching into the less dominant language.

## **Acoustic analysis**

### ***Background***

This acoustic analysis considers the potential mechanisms for code-switching pronunciation: 'blending' of the phonetic features of both languages and 'preparation' of articulatory gestures for production of a specific code-switched target. Experiment 2 suggested that Mandarin-English bilingual listeners are sensitive to some phonetic nuance in the acoustic signal leading up to sentence-medial Mandarin code-switches. The set of anticipatory phonetic cues for Mandarin code-switches could consist of a bundle of suprasegmental and segmental features. Given the difference in lexical tone between Mandarin and English, and Piccinini and Garellek's (2014) study showing intonation functioning as a cue, we will focus on the fundamental frequency of vocal fold vibration ( $f_0$ ), which is the primary acoustic correlate of perceived pitch.

We analyzed the pitch contours of all unspliced stimuli in both experiments, by using Praat (Boersma & Weenink, 2019) to extract  $f_0$  measurements between 75-600 Hz in 10 millisecond intervals from each sentence produced by the speaker. A check was conducted to randomly check automated data against manual measurements to ensure that the script output was accurate. The main comparison is between the unilingual English unspliced stimuli and the code-switched unspliced stimuli: If the pitch preceding English target words differs from the pitch preceding Mandarin code-switched target words, then pitch might be responsible for the differences in perception found in Experiment 2. If realized via 'blending', unilingual and code-switched pitch will generally differ. However, if realized via 'preparation', there will be target-specific differences between the pitch preceding English words and the pitch preceding Mandarin words of each tone, such as the mostly dissimilatory tone-specific anticipatory coarticulation found in unilingual Mandarin speech, e.g. lowering of pitch before the high level Tone 1 (Xu, 1997). If code-switched tonal coarticulation patterns with unilingual tonal coarticulation, then we will find dissimilatory anticipatory effects before all tones except the falling-rising tone 3. Alternatively, tonal coarticulation patterns in code-switched utterances might differ from the patterns in unilingual speech, since the English portion of the utterances is

unconstrained by lexical tone, whether assuming different contours or similar but more extreme contours.

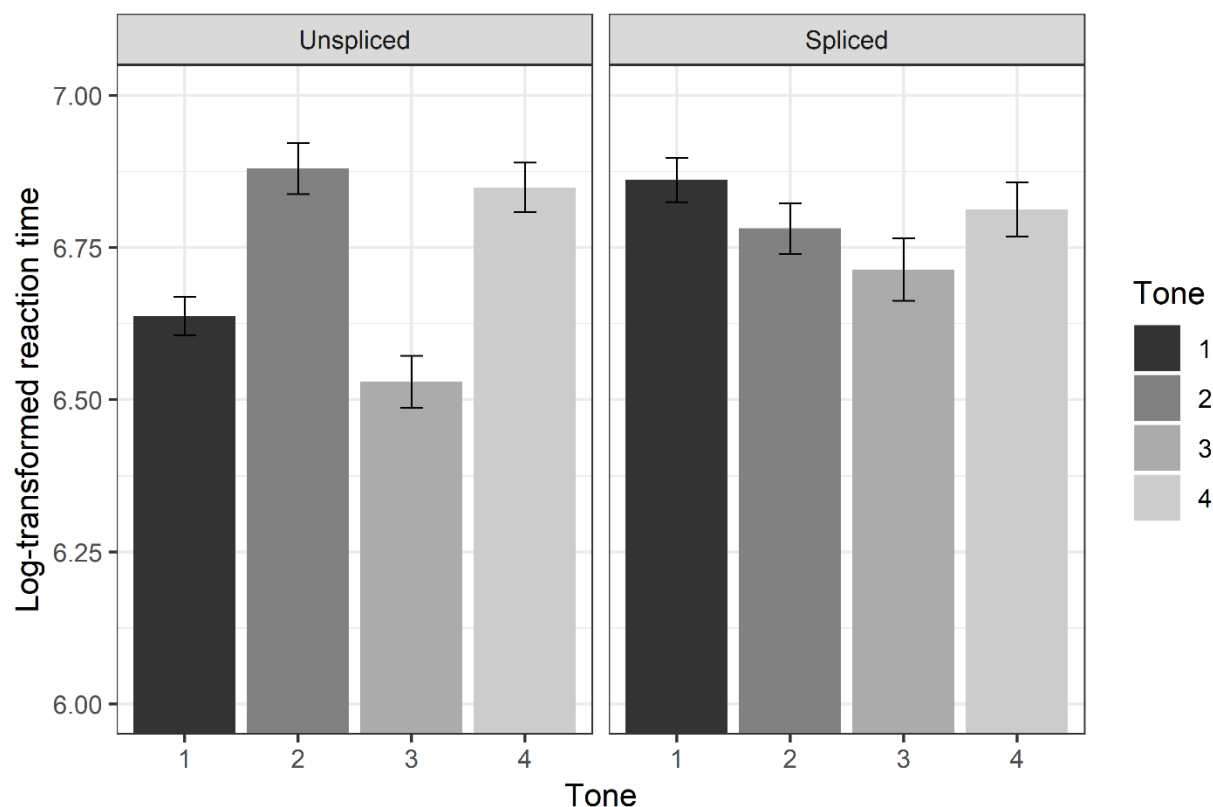
The 50 Mandarin target words were not balanced with respect to tone; Table 8 shows the number of Mandarin words that have initial syllables of each tone, by experiment.

	Experiment 1	Experiment 2	Total
Tone 1 (high level)	9	6	15
Tone 2 (rising)	8	4	12
Tone 3 (falling-rising)	6	3	9
Tone 4 (falling)	9	5	14

**Table 8.** Number of Mandarin words with tones 1-4 in each experiment. We analyzed the unspliced stimuli from each experiment separately, since only Experiment 2 showed a splicing effect for sentence-medial code-switches. The experiments used separate sets of stimuli and neither used stimuli balanced by Mandarin tone, which might have resulted in differences in  $f_0$  by experiment.

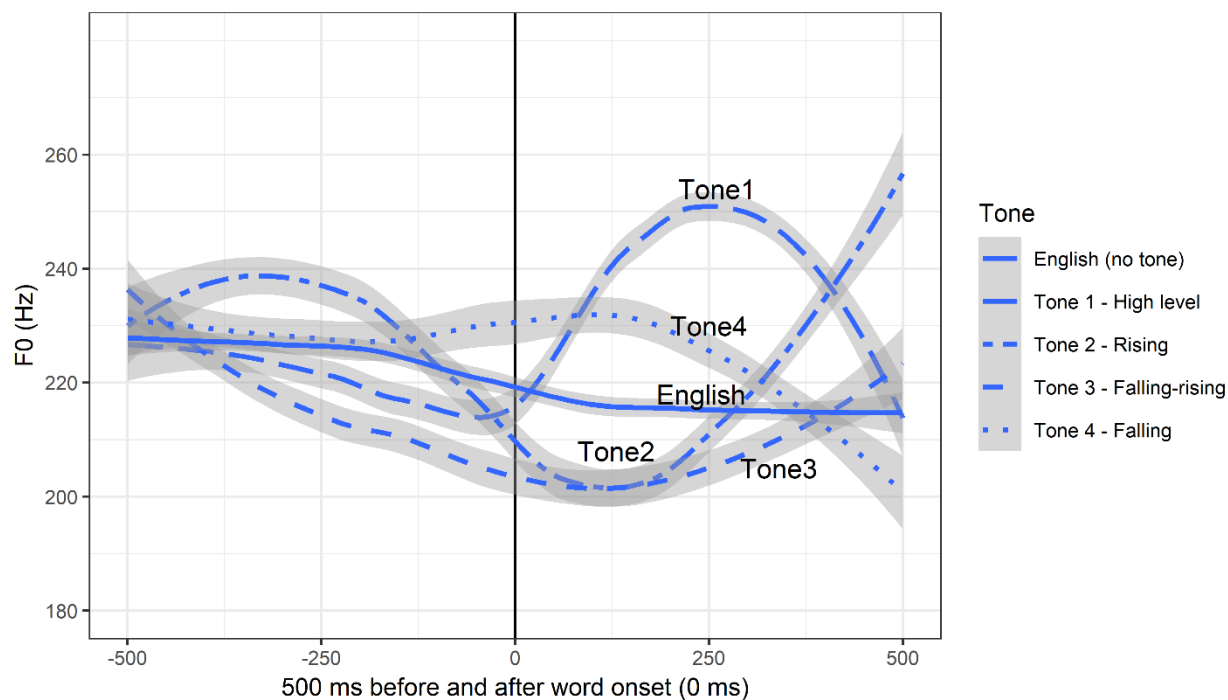
### *Acoustic analysis of Experiment 1 stimuli*

Experiment 1 found no splicing effect on reaction times to code-switched stimuli, so reaction times are plotted by target word tone to examine whether there might have been tone-specific differences in pronunciation (Figure 8). Sentence-medial and -final reaction times are averaged together since they showed the same general pattern, although there were no tone 3 sentence-medial words. Figure 8 indicates that reaction times to code-switches with tones 1 and 3 are visibly shorter when unspliced, while code-switches with tones 2 and 4 seem similar regardless of splicing, suggesting possible differences in cuing for tones 1 and 3 vs. 2 and 4.



**Figure 8.** Reaction times to code-switched stimuli in Experiment 1, by tone and by splicing condition.

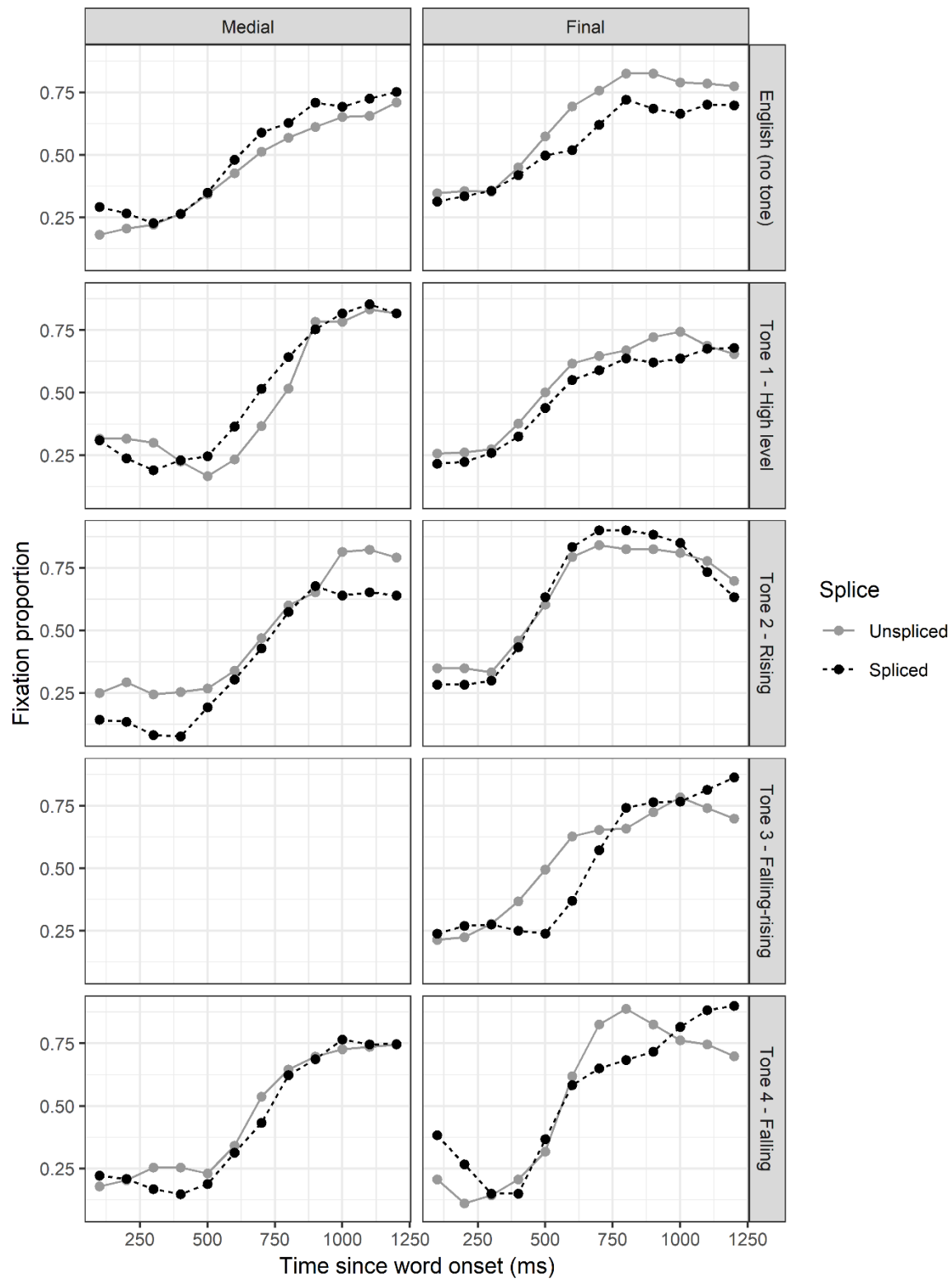
We plotted F0 measurements for 500ms before and after the target onset for unspliced stimuli from Experiment 1. Figure 9 shows evidence for a preparation mechanism, with tone-specific patterns such that the entire pitch contours before tones 2 and 4 are relatively high compared with before English targets, while the pitch contours before tones 1 and 3 are overall lower than the pitch contour before English targets. If listeners categorize pitch contours as high versus low, then English contours might be categorized with tone 2 and 4 contours, which would mean that code-switches of tones 1 and 3 might be cued to a greater degree than code-switches of tones 2 and 4. This is one possible explanation for the tone-specific reaction times in Figure 7 and the lack of a general splicing effect in the experiment.



**Figure 9.** Pitch contours for both medial and final unspliced stimuli in Experiment 1, by tone. Contours for code-switched stimuli are labeled by tone, and unilingual stimuli are labeled as English.

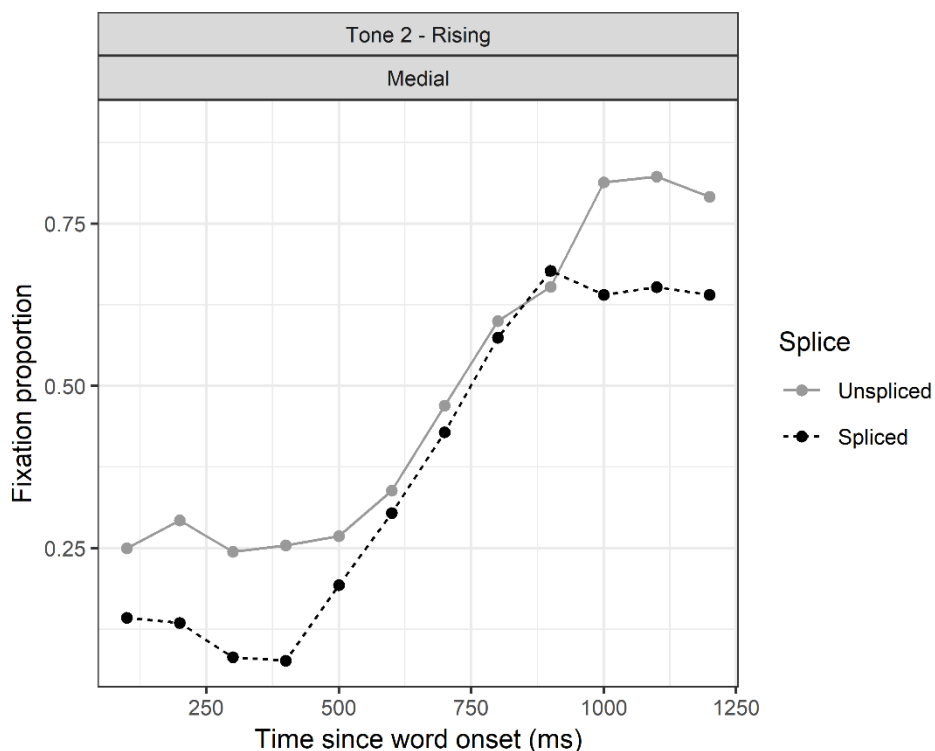
### *Acoustic analysis of Experiment 2 stimuli*

Experiment 2 found an effect of splicing, but only on sentence-medial code-switched targets, suggesting that phonetic cues can affect recognition depending on word position. We plotted looks to target by both position and tone of the target word in Figure 10, to determine whether cuing might vary by position and tone as well.



**Figure 10.** Raw data for looks to target, by position and tone, across all participants and trials, in Experiment 2. There were no sentence-medial target words with tone 3.

Figure 11 plots an instance of listeners looking more toward unspliced than spliced sentence-medial code-switched targets: those with tone 2. When comparing sentence-medial code-switched targets of all tones, this pattern is only present for tone 2 and 4 targets, as seen in Figure 10. However, listeners look more toward sentence-final targets of nearly all tones when they are unspliced.



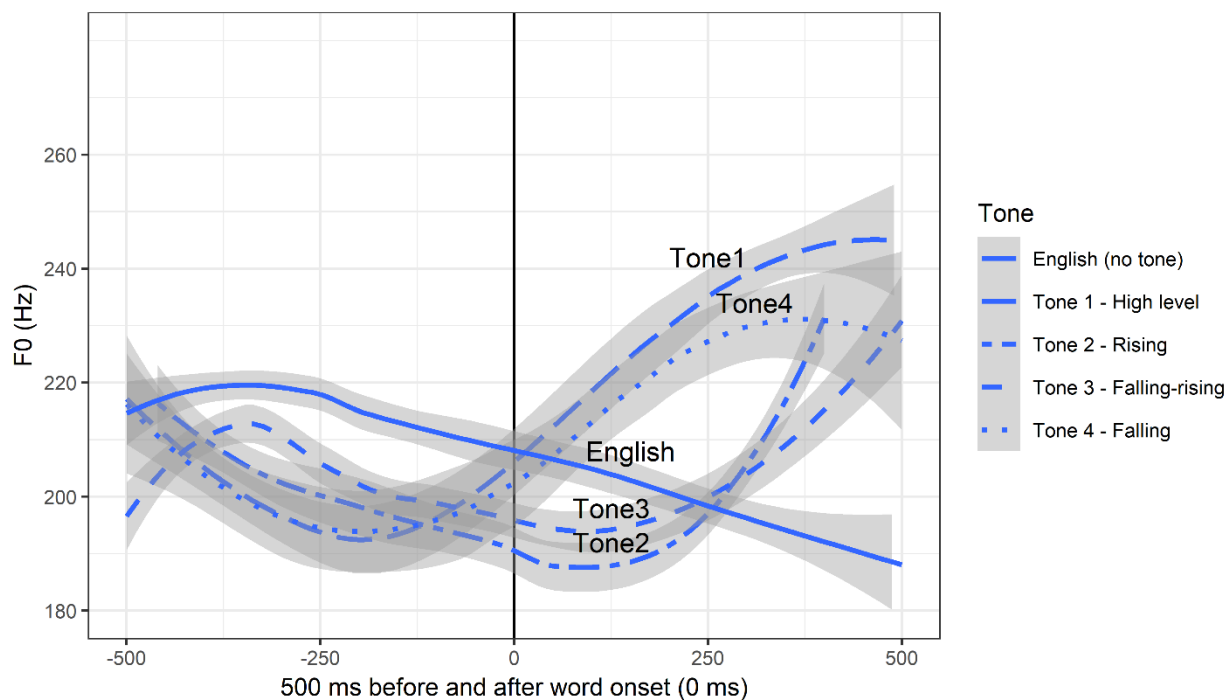
**Figure 11.** Raw data for looks to sentence-medial code-switched (Mandarin) tone 2 targets, across all participants and trials.

The  $f_0$  of these stimuli are plotted by tone, with sentence-final targets in Figure 12 and sentence-medial targets in Figure 13. There were no sentence-medial tone 3 words. Both figures provide evidence for a preparation mechanism of code-switching pronunciation of  $f_0$ . The shape and trajectory of the pitch contours depend on the tone in the upcoming target, for stimuli in Experiment 2.

Figure 12 shows either reduced or absent tonal coarticulation into sentence-final code-switched targets. The pitch contour before final English words was higher than before any of the Mandarin tones, across the entire 500ms duration before target onset. The  $f_0$  range for pitch contours is also below 220 Hz, in contrast to pitch contours before sentence-medial words, which occur above 220 Hz. This lower  $f_0$  range could have acted as a cue to the listener that the sentence was nearing its end: if the participant has heard the entire main clause with no mention of any pictured objects, then process of elimination and lower  $f_0$  should lead them to expect a sentence-final target. Additionally, all of the Mandarin tones on the code-switched targets had a rising contour, including tone 4, which should be a falling tone. In contrast, the  $f_0$  of final English targets slopes downwards. If listeners categorize contours as rising or falling, then this

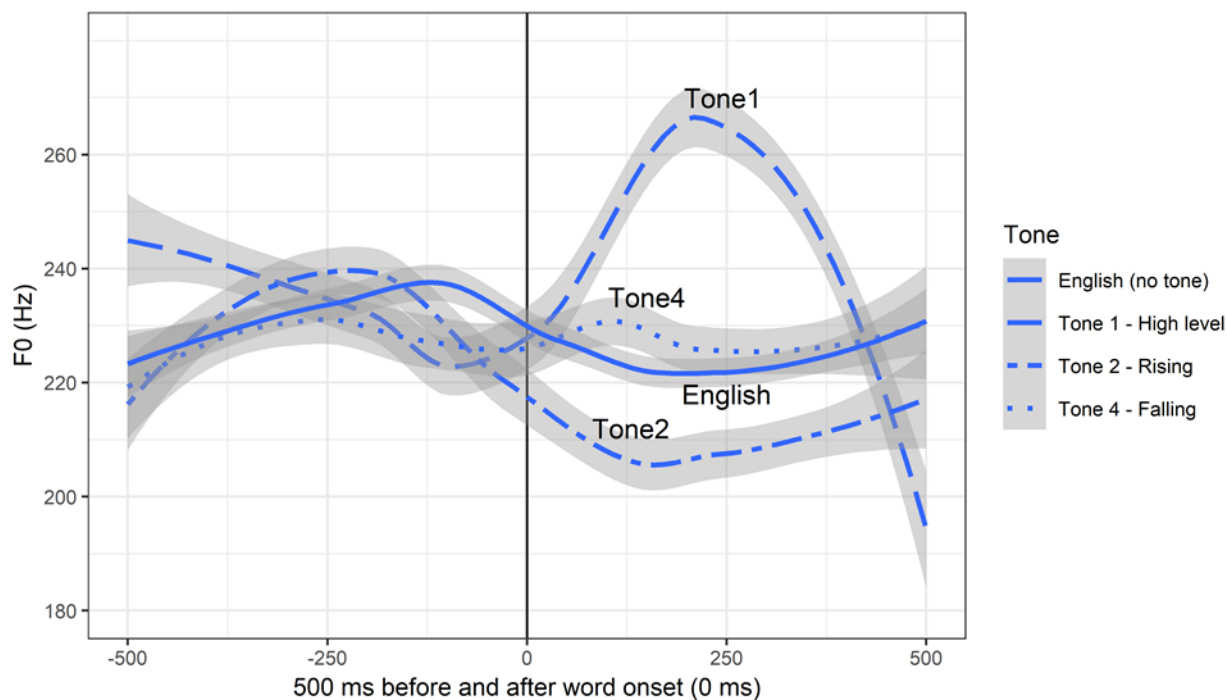


difference of  $f_0$  on the target words themselves might have contributed to the Experiment 2 result that showed no splicing effect on sentence-final code-switched stimuli.



**Figure 12.** Pitch contours for sentence-final unspliced stimuli in Experiment 2, by tone. Contours for code-switched stimuli are labeled by tone, and unilingual stimuli are labeled as English.

Figure 13 demonstrates the expected dissimilatory anticipatory tonal coarticulation patterns for sentence-medial Experiment 2 stimuli, but with no obvious difference between the pitch contours preceding tones 2 and 4 and those preceding tone 1, despite the former receiving more looks when unspliced. Pitch therefore might not be the primary phonetic cue; segmental cues might be playing a larger role, especially since some competitors differ slightly in onset, e.g., voiceless retroflex fricative in Mandarin vs. voiceless post-alveolar fricative in English.



**Figure 13.** Pitch contours for sentence-medial unspliced stimuli in Experiment 2, by tone. Contours for code-switched stimuli are labeled by tone, and unilingual stimuli are labeled as English.

### Summary

This exploratory acoustic analysis suggests that code-switching pronunciation of  $f_0$  depends on the tone of the Mandarin code-switch and whether the code-switch is sentence-medial or -final. This points to a preparation explanation of code-switching pronunciation, as realization of anticipatory  $f_0$  contours depends on aspects of the target, rather than characteristics of the language. Nevertheless, a blending mechanism is not completely ruled out as we do not have unilingual Mandarin productions to compare with the unilingual English productions.

The role of code-switching pronunciation of  $f_0$  as an anticipatory phonetic cue to code-switching is difficult to determine through this analysis. While the eye tracking results suggest that sentence-medial code-switches are more easily processed when phonetic context is retained, the  $f_0$  contours before these target code-switched stimuli do not seem to exhibit any obvious cue-like features. Regardless, listeners are evidently sensitive to something in the acoustic signal, so this is work for future studies investigating the phonetic features of Mandarin-English code-switching pronunciation, with stimuli balanced across each Mandarin tone.

### General discussion

Using concept monitoring and eye tracking experiments, we found evidence for a switch cost in Mandarin-English code-switches. Crucially, we also found that phonetic cues mitigated switch cost in sentence-medial switches.

The finding of a switch cost in auditory word recognition is consistent with previous studies: Soares and Grosjean (1984) found that English-Portuguese bilinguals took longer to recognize code-switched words in carrier sentences in a lexical decision task. Similarly, Olson

(2017) found longer fixation times in Spanish-English code-switched vs. unilingual sentences in one experimental condition (the ‘monolingual language mode’, i.e., stimuli with few switches). We found, in our concept monitoring task, that Mandarin-English bilinguals took longer to respond to Mandarin code-switched words. The similarity of our results with those in the monolingual language mode condition in Olson’s (2017) study, combined with the fact that our code-switched targets were syntactically integrated in the English matrix sentences, invites the question of whether they were phonologically integrated into the English context, i.e., whether they were more similar to language borrowings or to nonce borrowings (Cacoullos & Aaron, 2003; Poplack & Dion, 2012). Although there are no unilingual Mandarin utterances from our speaker for comparison, the acoustic analysis suggests that the Mandarin tone contours were intact. Hence, our stimuli could not be considered either type of borrowing.

The reaction times to the (off-line) concept monitoring task did not reveal any benefit of retaining the phonetic context leading up to code-switches, but eye-tracking did: There were more looks to sentence-medial code-switches when the phonetic context was present. These results suggest that the phonetic context can facilitate the recognition process as it unfolds, but that it does so to different degrees in different contexts (medial vs. final).

Our acoustic analyses may shed some light on the mechanisms underlying the pronunciation of code-switched utterances. We proposed in the Introduction that acoustic properties of code-switched targets may arise as a result of ‘blending’ of two phonetic systems on the one hand and of ‘preparation’ for the target pronunciation on the other. A key difference between these two possibilities is that the ‘preparation’ scenario, but not the ‘blending’ scenario, leads one to expect the pronunciation of the region preceding the code-switched target to depend primarily on the specific target. Our acoustic analyses revealed that the phonetic context preceding code-switches depended on the target word’s lexical tone: We observed dissimilatory anticipatory tonal coarticulation before tones 1, 2, and 4, and assimilatory coarticulation before tone 3. We regard these observations to be tentative, because of the small numbers of items. If the pattern we observed can be confirmed with a larger set of items of each tone, it would suggest the presence of target-specific code-switching pronunciation. Such target-specific tonal coarticulation would be expected under the ‘preparation’ account of phonetic cues to code-switching, rather than the ‘blending’ account.

It is impossible to say, on the basis of the available data, which aspects of tonal coarticulation -  $f_0$  contours, range, and/or extrema, or other suprasegmental and segmental features - might act as phonetic cues. We regard this as a question for future research.

The position-dependent (medial vs. final) pattern we observed has theoretical and methodological implications. Recognition of code-switches, as with words in unilingual utterances, might be affected by lexical content, structural position, contextual information, etc., all of which might affect switch cost. Sentence-final code-switched targets might additionally be cued by the gradual lowering of  $f_0$  present throughout all of our English sentences signaling the end of the stimulus and a last possible location for the target to occur. Information structure and task demand might therefore result in no cost to recognizing a code-switch at the end of a sentence, since the position of a final target word becomes more and more predictable as the utterance progresses.

A limitation of this study is a possible confound between splicing and the effect of withholding phonetic cues. Our splicing manipulation was confined to identity-splicing unilingual English sentences and cross-splicing Mandarin code-switches into English sentences that were originally unilingual. A complete splicing design would also include cross-splicing

English words into code-switched sentences and identity-splicing Mandarin code-switches into code-switched sentences. As the study stands, any code-switched stimuli that are spliced also lack anticipatory phonetic cues to a code-switch. The inclusion of spliced code-switched stimuli that retain phonetic cues (i.e., identity-spliced code-switched sentences) would allow a more certain assessment of whether it was purely withholding phonetic cues that resulted in slower bilingual recognition of the code-switch. The tone-specific patterns we observed argue against a uniform effect of splicing. Nevertheless, a complete splicing paradigm would be desirable, for teasing apart effects of splicing and tonal coarticulation for each target tone and sentence position.

## **Conclusion**

Our study adds to previous literature on phonetic reflexes and cuing of code-switches, in showing that removing the preceding phonetic context through splicing can make recognition of a code-switch more difficult in certain contexts. Thus, the present study contributes to a rapidly growing body of literature investigating whether code-switches must necessarily incur a processing cost for listeners. It is becoming apparent that phonetic cues play a role in code-switched recognition (Piccinini & Garellek, 2014; Fricke et al., 2016), though this sensitivity depends on the phonetic features of the languages being switched. Previous studies have indicated the facilitatory role of phonetic cues on recognition of a code-switch, and we have further shown that Mandarin-English bilingual listeners can be negatively affected by the removal of phonetic cues, as listeners expect to continue hearing the matrix language unless they are given phonetic reasons to expect otherwise. Mandarin-English bilinguals are sensitive to code-switching pronunciation, and pitch is possibly one of many interacting anticipatory phonetic cues to a code-switch.

## Chapter 3. Investigating asymmetric switch costs in auditory comprehension

### Introduction

Many studies on code-switching have found a switch cost, or increased processing difficulty with code-switched words compared to unilingual words. When these studies compare the processing cost of code-switching in each direction (i.e. from Language A to B vs. B to A), a consistent finding has been that switch costs are asymmetric, meaning that switching in one direction is more costly. Such asymmetric switch costs have most often been observed in production (e.g., Meuter & Allport, 1999; Costa & Santesteban, 2004), with much less evidence available in auditory comprehension, though the only known study that compares switching in both directions also found an asymmetric switch cost (Olson, 2017).

Models such as the Inhibitory Control Model (ICM) theorize that switch costs arise from the process of language control, which is essentially the bilingual problem of needing to select the appropriate language during speaking and listening. Code-switching, particularly intrasentential switching, exacerbates that need, with the bilingual simultaneously managing both languages. The ICM addresses bilingual language production, postulating that producing the dominant language requires more inhibition, so that switching back into it is more costly than switching into the non-dominant language (Green, 1998). The ICM does not directly address comprehension, and the asymmetric switch cost found in the low switch rate condition of Olson's (2017) Spanish-English study is insufficient evidence to extend the ICM's predictions to auditory comprehension.

In fact, in the previous chapter, the effect of dominant language was different from the ICM's predictions: Mandarin-dominant bilinguals recognized Mandarin code-switched words more quickly than English-dominant bilinguals in both tasks. However, a further comparison of Mandarin and English code-switches is necessary to adequately investigate whether any sort of asymmetric switch cost might be present in Mandarin-English bilingual auditory comprehension. This chapter will investigate several possible reasons for an asymmetry.

Natural asymmetries occur in bilingualism. For example, it is unlikely that anyone is truly a "balanced bilingual," as pointed out by Grosjean (1985; 1989). Each bilingual might have slightly greater proficiency in one language, acquired one language earlier than the other, feel more comfortable speaking one language, or interact in one language more often than in the other. Changes in our social or linguistic environment, such as residing in a primarily monolingual community, can also contribute to one language being more dominant than the other, so that language dominance can shift over time.

Natural asymmetries can occur in code-switching as well. When bilinguals are speaking in Language A, they might frequently insert words from Language B, but the reverse (inserting Language A words into Language B sentences) may not occur as frequently. Moreover, during code-switching, the phonetics of one language might influence the pronunciation of the other to a greater extent than the reverse. Therefore, natural asymmetries – such as language dominance, frequency of insertion by language, and phonetic patterns – might translate into processing asymmetries.

First, language dominance may contribute to an asymmetric processing cost in auditory comprehension. But the nature of this asymmetry is unclear. Given previous literature on language production, we might predict a processing asymmetry that results from the need to regulate which language is more activated: the dominant language is stronger and therefore must

be more heavily inhibited, resulting in a greater processing cost when switching back into it. On the other hand, studies in auditory comprehension have shown mixed results. In this study, I operationalize language dominance in terms of proficiency, history, attitudes, identity, and use (Birdsong, Gertken, & Amengual, 2012), which are domains of natural asymmetry in bilingual individuals. Often, bilinguals might spend more time in an environment where one language is used, or identify more strongly with the culture of one language. Mandarin-English bilinguals who attend the University of California Berkeley might have to interact more often in English, the language of instruction; however, the California Bay Area is a distinct bilingual environment that likely contributes to aspects of these bilinguals' language dominance.

Another natural source of asymmetry comes from differences in the frequency of switching from one language into the other mid-sentence. In Mandarin-English bilingual speech, switches from English to Mandarin intrasententially, including within a noun phrase, are grammatical but infrequent compared to Mandarin-to-English switches (Lu, 1991; Ong & Zhang, 2010). If experience affects processing, then more frequently encountered types of code-switches will be easier to recognize. Thus, English code-switches in Mandarin sentences might be easier to recognize than Mandarin code-switches in English sentences.

Finally, code-switches might be cued to different degrees, resulting in asymmetrical cuing. The phonetic reflexes of code-switching are not necessarily bidirectional. For example, research on languages with different voice onset time (VOT) ranges has largely shown unidirectional influence of the short lag VOT language on the long lag VOT language during code-switching, such as Spanish on English, or Greek on English (Antoniou et al., 2011; Goldrick et al., 2014; Balukas & Koops, 2015; Piccinini & Arvaniti, 2015; Olson, 2016). If English VOT – which is long lag – shortens but Spanish VOT does not change, then a switch from Spanish into English might not be strongly cued, since Spanish VOT would be unchanged and sound no different from in a unilingual Spanish utterance. On the other hand, a switch from English into Spanish would be cued by the shortened English VOT that sounds gradually more and more Spanish-like leading up to the Spanish code-switch.

Similarly, with Mandarin-English code-switching, shifts in  $f_0$  might differ depending on the direction of the switch. In the previous chapter, retaining the naturally occurring phonetic context of stimulus sentences aided listeners in recognizing sentence-medial Mandarin code-switched words in English sentences. The acoustic analysis of those stimuli revealed tone-specific pitch patterns preceding Mandarin code-switches, suggesting a possible role of  $f_0$  in anticipatorily cuing upcoming code-switches. However, Mandarin-to-English code-switching has not yet been studied, and it is unclear what pitch patterns might occur preceding English code-switches.

Phonetic cuing in bilingual recognition might therefore be dependent on the patterns in bilingual production. Unidirectional phonetic transfer might result in stronger cuing for one direction of code-switching than the other, resulting in an asymmetric switch cost in auditory comprehension. Even cases of bidirectional phonetic transfer, where there is more influence of one language on the other than vice versa, might result in imbalanced cuing. Moreover, phonetic transfer might only result in a small or imperceptible phonetic shift, so that cuing is dependent on the degree or extent of phonetic transfer as well as the listener's sensitivity to subtle acoustic changes.

To investigate potential anticipatory phonetic cues, we will focus on  $f_0$ , since it is likely to have a strong weight due to the presence of lexical tone in Mandarin but not English, though the bundle of potential phonetic cues can consist of multiple segmental and suprasegmental

features. If code-switching between Mandarin and English is subject to bidirectional phonetic transfer, then English might influence Mandarin such that Mandarin tones are dampened, and Mandarin might influence English such that English varies slightly more in pitch. Subsequently, listener sensitivity would allow these phonetic patterns to function as cues for both directions of code-switching. But if phonetic transfer is stronger in one direction than the other, or if code-switching between Mandarin and English is characterized by unidirectional phonetic transfer, then one direction of code-switching might be cued more strongly than the other. An acoustic analysis will examine the pitch of the speaker's productions, comparing  $f_0$  measurements preceding Mandarin and English code-switches to  $f_0$  measurements preceding target words in comparable unilingual utterances.

Therefore, this study will investigate the influence of (1) dominant language, (2) frequency of switch direction, and (3) phonetic cuing on switch costs in auditory comprehension. Each of these three factors has the potential to give rise to an asymmetric switch cost in a visual world eye-tracking experiment paired with English and Mandarin auditory stimulus sentences with or without code-switched target words.

### *Hypotheses*

I hypothesize that dominant language, frequency of switch direction (Mandarin-to-English vs. English-to-Mandarin), and phonetic cuing will affect the auditory comprehension of code-switches, potentially resulting in an asymmetric switch cost.

First, the ICM leads to the prediction that dominant language code-switches will incur a greater processing cost than non-dominant language code-switches. In the eye-tracking experiment, this would be reflected through fewer looks to targets that correspond to code-switches in the dominant language than in the non-dominant language. For instance, there would be fewer looks toward images corresponding to Mandarin code-switches when the participant is a Mandarin-dominant bilingual. However, if the results of Experiment 2 are replicated, then non-dominant language code-switches will incur a greater processing cost.

Second, if experience with code-switching affects recognition, then more frequent code-switches will incur a smaller cost. In this case, we would expect that Mandarin code-switches will incur a greater processing cost than English code-switches, because the insertion of Mandarin words into English sentences occurs less frequently than the insertion of English words into Mandarin sentences.

Third, assuming any subtle phonetic changes that occur as a result of code-switching are always perceptible, if there is unidirectional phonetic transfer, then the language being influenced might phonetically cue the other language to a greater degree than the reverse during code-switching. For example, the VOTs of long-lag VOT languages tend to shorten, while the VOTs of short-lag VOT languages do not tend to lengthen, during code-switching between both types of languages. In such cases, where there is unidirectional phonetic transfer from the short-lag VOT language to the long-lag VOT language, I hypothesize that only code-switches in the long-lag VOT language would be cued, with the asymmetric cuing thus resulting in asymmetric switch costs. Alternatively, if bidirectional phonetic transfer does occur, but is more perceptible in one direction than the other, this might result in asymmetric cuing as well. That would then lead to asymmetric switch cost, with the code-switch that is phonetically cued to a greater degree incurring a smaller processing cost. For example, if the phonetic patterns characterizing switching from English into a Mandarin word are less perceptible than those characterizing

switching from Mandarin into English, then Mandarin code-switched words will incur a greater processing cost.

To ascertain whether code-switches are being anticipatorily cued, and whether any cues affect recognition, looks to targets on trials where stimuli that have been manipulated to withhold the preceding phonetic context will be compared to those on trials where stimuli retain that context. If there is anticipatory phonetic cuing that affects switch cost, then code-switches on trials with stimuli that withhold phonetic context will incur a greater processing cost.

In the experiment in the previous chapter, only Mandarin code-switches in English sentences were examined, and cuing was evaluated by cross-splicing Mandarin code-switches into originally unilingual English sentences and controlled for by identity-splicing English words into English sentences. In the current experiment, this splicing manipulation is updated to fully control for effects of cuing vs. splicing: both unilingual and code-switched stimuli in each language can be either unspliced, identity-spliced, or cross-spliced. Cross-splicing code-switched stimuli is intended to withhold anticipatory phonetic cues to the code-switched target, which is expected to result in more processing difficulty.

## **Method**

### ***Speaker***

A 31-year-old female Mandarin-English bilingual produced the auditory stimuli for this experiment. She acquired Mandarin from birth and English at age 13. She self-reported using both languages equally with friends, primarily Mandarin with family, and primarily English in school. On the Bilingual Language Profile (Birdsong et al., 2012), she self-rated her proficiency as 6 on a scale of 1 (not well at all) to 6 (very well) in speaking, understanding, reading, and writing proficiency in both languages. Her BLP score was -8, which being close to 0 on a scale from -218 to 218 where the extremes indicate strong dominance in one language, indicates that she is a balanced bilingual who is very slightly dominant in Mandarin. On a code-switching questionnaire, she reported code-switching on a daily basis, though only doing so with friends.

### ***Participants***

#### ***Screening***

Participants were screened via an online form prior to the experiment, to ensure they spoke Mandarin and English, and self-rated at least 3 on a scale of 1 (low) to 4 (high) on the question screening for speaking and understanding proficiency. Moreover, reading proficiency in either Mandarin characters or pinyin was required, as the familiarization task preceding the main experiment required reading English and Mandarin words.

In the lab, participants were screened a second time to ensure they had sufficient vocabulary in both languages to complete the experiment. They were given a familiarization task during which they were presented the 148 visual stimuli from the experiment one by one on a computer screen. Along with each colored line drawing, the printed English and Mandarin (characters and pinyin) names appeared below the picture. The task was self-paced, and participants were given an index card to note down any words they were unfamiliar with or would not use to describe an object (e.g. due to dialectal lexical differences). If the participant



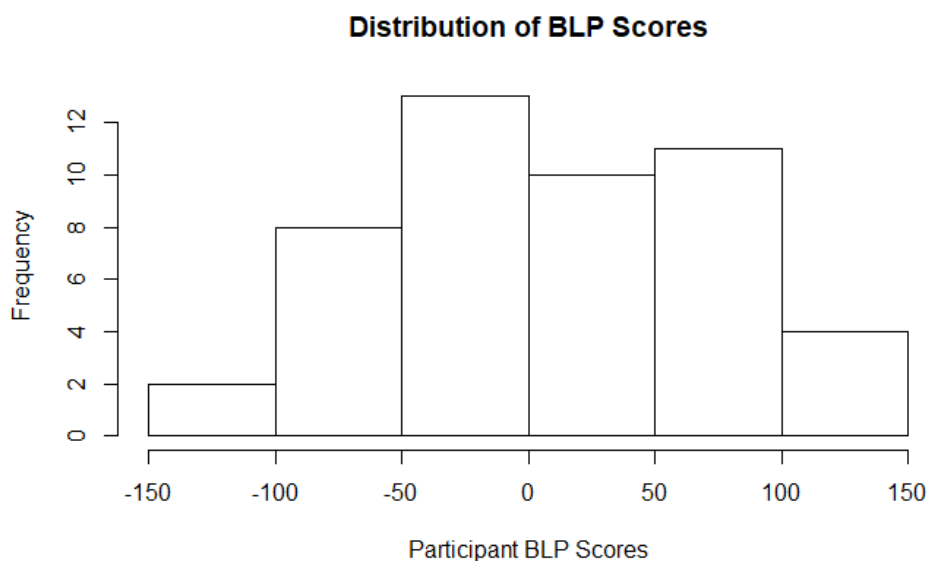
did not recognize 20 or more Mandarin or English words for the pictures, they were disqualified from the experiment.

### *Language background*

54 bilingual speakers of Mandarin Chinese and English with no speech or hearing defects qualified to participate in this experiment. Five participants' data were discarded due to technical issues during the experiment, and one participant's data was discarded because their language forms were not completed. Thus, the data of 48 participants (35F, 13M) were analyzed.

Participants' linguistic backgrounds varied, according to the responses they gave on two questionnaires. The first was the Bilingual Language Profile (Birdsong et al., 2012), which they could choose to complete in Mandarin or English. This profile asks about participants' language history, proficiency, attitudes, and behavior, and quantifies their scores on a scale from -218 to 218, with negative scores indicating Mandarin-dominance and positive scores indicating English-dominance. Scores near 0 indicate similar dominance in both languages, or what has traditionally been referred to as a "balanced bilingual." The second was a code-switching questionnaire asking about code-switching attitudes and behavior (Appendix D).

Just less than half of participants (N=23) scored as Mandarin-dominant on the BLP, while the rest (N=25) scored as English-dominant. The participants' scores ranged from -118 to 125, with an average of 7.8 (SD=62). Therefore, participants were distributed fairly evenly in terms of language dominance, as can be seen in Figure 14 below.



**Figure 14.** Distribution of BLP language dominance scores. Negative scores indicate Mandarin-dominance while positive scores indicate English-dominance.

All of the Mandarin-dominant bilinguals acquired Mandarin as their L1. The English-dominant bilinguals varied, with half being simultaneous L1 speakers of Mandarin and English (N=12), few L1 English speakers (N=2), and many L1 Mandarin speakers (N=9). One English-dominant bilingual acquired only Cantonese as the L1. Another English-dominant bilingual reported acquiring English and Mandarin at age 3 and 4 respectively but did not report speaking any other languages from childhood. This summary is based entirely on BLP self-reporting; on a

separate screening questionnaire, many participants indicated that Cantonese was also their L1. The majority of participants were born either in the US or China. Six were born in Hong Kong, 3 in Taiwan, and 1 each in Brazil, Austria, Macau, and New Zealand.

Table 9 provides participants' average age of acquisition of English and Mandarin, along with their self-rated proficiency scores in each language on a scale of 0 – 6, where 0 means “not well at all” and 6 means “very well.” Generally, participants self-ratings in speaking and understanding were similar across both languages, but participants self-rated as more proficient in reading and writing English.

	<b>English Mean (SD)</b>	<b>Mandarin Mean (SD)</b>
<b>Age of acquisition (yrs)</b>	3.60 (3.33)	0.35 (1.02)
<b>Self-rated speaking</b>	5.46 (0.85)	5.33 (0.86)
<b>Self-rated understanding</b>	5.67 (0.72)	5.6 (0.68)
<b>Self-rated reading</b>	5.56 (0.92)	4.75 (1.55)
<b>Self-rated writing</b>	5.54 (0.87)	4.42 (1.71)

**Table 9.** Participants' self-rated proficiency from 0 (not well at all) to 6 (very well) on BLP.

On the code-switching questionnaire, which asked specifically about participants' code-switching habits and experience, the 21 Mandarin-dominant participants reported code-switching relatively often, self-reporting an average of 3.24 (SD=1.3) on a scale of 1 (never) – 5 (always). The 27 English-dominant participants reported a slightly lower average of 2.67 (SD=1.1). When asked about frequency of insertion by language, the majority of participants, 30 out of 48, reported a higher number on a 1 – 5 scale for inserting English words into Mandarin sentences (the more frequent direction of code-switching, according to previous studies) than Mandarin words into English sentences. Sixteen of the 48 total participants reported inserting words in both directions equally, with 7 of them being Mandarin-dominant and 9 English-dominant. Only 2 participants, both Mandarin-dominant, reported more frequently inserting Mandarin words into English sentences (the infrequent direction of code-switching). Thus, these bilingual participants' code-switching experiences reflect the experiences of most Mandarin-English bilinguals in the U.S., which studies have shown are more likely to insert English words into Mandarin sentences than Mandarin words into English sentences (Lu, 1991; Ong & Zhang, 2010).

## **Materials**

### *Visual stimuli*

The 148 visual stimuli were colored line drawings of common objects from the Rossion and Pourtois (2004) database, or other visually similar public domain images, which were corrected for brightness and color, and sized to the same dimensions as the database pictures. The pictures were displayed in the experiment via a visual world paradigm (Huettig, Rommers & Meyer, 2011), such that four pictures appeared on the screen for any given trial. Seventy-four

pictures corresponded to experimental target words, with 37 functioning as targets for English sentences and 37 for Mandarin sentences. The other 74 pictures always corresponded to competitors and distractors in the visual world paradigm. The words corresponding to the sets of visual world images can be found in Appendix E.

### *Auditory stimuli*

The auditory stimuli consisted of 74 sentences: 37 English sentences and 37 Mandarin sentences. Of the English sentences, 19 were unilingual English sentences with English target nouns, and 18 were code-switched English sentences with Mandarin target nouns. Of the Mandarin sentences, 18 were unilingual Mandarin sentences with Mandarin target nouns, and 19 were code-switched Mandarin sentences with English target nouns.

The target nouns in the sentences corresponded to the visual stimuli in the experiment. These target nouns were located in a variety of sentence-medial or -final positions, but never sentence-initially. Sentences were constructed so that the context preceding the target noun would not provide semantic cues as to the identity of the target. Therefore, target nouns in an English sentence were immediately preceded by a (definite or indefinite) article or a possessive pronoun. Target nouns in a Mandarin sentence were preceded by a verb or a possessive particle. While Mandarin has no indefinite articles, nouns can be preceded by numerals, measure words, and classifiers, or occur as bare nouns. Measure words and classifiers are dependent on the noun, so they were avoided; consequently, target nouns in Mandarin sentences were preceded by relatively semantically neutral verbs (e.g. “saw,” “liked”) and possessive particles. These sentences can be found in Appendix F.

### *Stimulus norming*

To ensure that the entire preceding sentence context – not just the immediately preceding word – was indeed semantically congruous for all four objects in the visual world, sentences were normed via an online task with a separate group of Mandarin-English bilinguals.

For this norming study, a multiple-choice online questionnaire was created, such that, for each experimental stimulus, the portion of the sentence preceding the target noun was the prompt, and the nouns corresponding to the four pictured objects (target, competitors, and distractor) served as the choices. Participants were asked to choose the word they thought was most likely to follow the sentence context. All sentences and choices were presented in the language of the sentence, not the target noun.

Thirteen Mandarin-English bilinguals (11 F, 2 M) participated in the norming study. They were screened via a language background questionnaire containing comprehension checks to ensure they were actual speakers of Mandarin and English. Their averaged self-ratings of Mandarin and English proficiency on a scale of 1 (low) to 4 (high) are shown in Table 10 below.

	English	Mandarin
Speaking	3.85 (0.55)	3.77 (0.44)
Understanding	3.92 (0.28)	3.77 (0.44)
Writing	3.77 (0.6)	3.31 (0.95)
Reading	3.92 (0.28)	3.62 (0.65)

**Table 10.** Norming study participants' self-ratings of English and Mandarin proficiency on 1 (low) to 4 (high) scale.

For each sentence, the number of participants who chose the target noun as most likely to occur with its preceding sentence context was divided by the total number of participants, to obtain a predictability ratio. A ratio of 0.25 would indicate that the probability that participants chose the target noun was by chance. The overall results indicate that the stimuli are generally semantically unpredictable based on preceding context (mean = 0.26; SD = 0.19).

### *Splicing*

The availability of phonetic cues to upcoming code-switches was controlled by means of a splicing manipulation, as follows: The speaker recorded unilingual and code-switched versions of all English and Mandarin sentences. Stimuli were constructed in one of three ways: (a) unspliced: recorded sentence used as is, (b) identity-spliced: the target noun from one recording was combined with the frame from a second recording identical in content (i.e. also unilingual or also code-switched), and (c) cross-spliced: the target noun from recording was combined with the frame from a linguistically non-identical second recording (i.e. code-switched if the first recording was unilingual, and vice versa).

To construct a code-switched sentence stimulus via cross-splicing, we used the target word from a code-switched recording and the frame from a unilingual recording of that same sentence. For example, the word “帽子” [mau<sup>51</sup>tʃi] from “We didn't really think that we would find a 帽子 in a tree in our yard” was combined with the frame “We didn't really think that we would find a ... in a tree in our yard” from the unilingual “We didn't really think that we would find a mouse in a tree in our yard.” The word that occurred in place of the target in the unilingual recording (e.g. mouse [maʊs] instead of 帽子 [mau<sup>51</sup>tʃi]) was chosen to have a similar onset as the target, for ease of splicing. The extracted target and frame were combined into a different spliced version of “We didn't really think that we would find a 帽子 in a tree in our yard.” Code-switched sentence stimuli constructed through cross-splicing contain code-switched targets that are not preceded by anticipatory phonetic cues to code-switching, since any naturally occurring phonetic cues have been withheld via splicing.

Unilingual stimuli were constructed via cross-splicing as well, using the target word from a unilingual recording and the frame from a code-switched recording of the same sentence. The word that occurred in place of the target in the code-switched recording also had a similar onset as the target. Cross-spliced unilingual stimuli serve as a control so that some unilingual stimuli also go through the cross-splicing process, to ensure that any effects in the results are not due to the cross-splicing process rather than cuing.

To construct a code-switched sentence stimulus via identity-splicing, two recordings of the same sentence were used, combining the target word from one with the frame from the other. For example, from two recordings of “We didn't really think that we would find a 帽子 in a tree

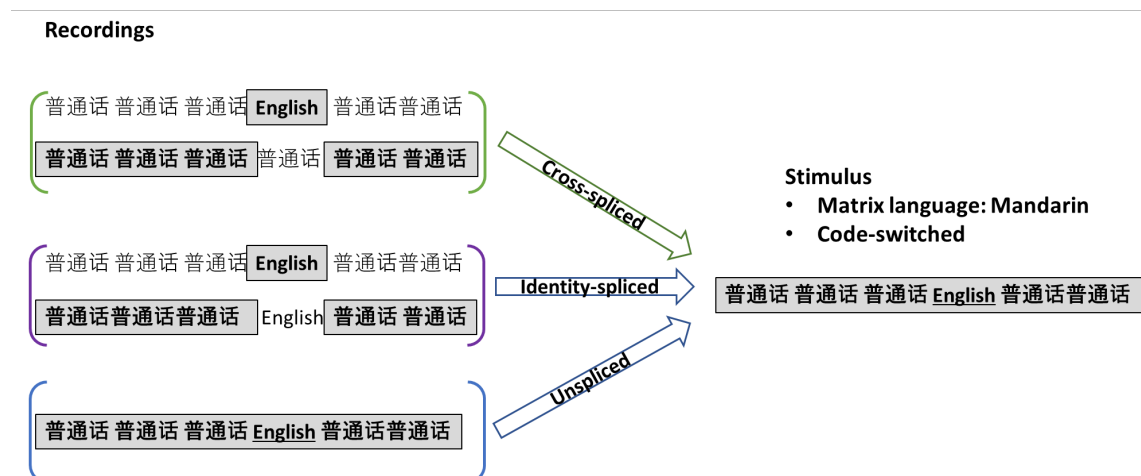
in our yard,” the “帽子” [ was taken from one and the “We didn’t really think that we would find a ... in a tree in our yard” was taken from the other. The extracted target and frame were then combined into a spliced version of “We didn’t really think that we would find a 帽子 in a tree in our yard.” The sentence intonation of both recordings was checked to ensure the same words were stressed in each. Identity-spliced code-switched stimuli serve as a control to which cross-spliced code-switched stimuli can be compared, to ensure that any effects in the results are due to withholding phonetic cues and not the splicing process, since we can compare two types of spliced code-switched stimuli, one retaining cues despite splicing and one not.

Figure 15 and Figure 16 illustrate how Mandarin and English sentence stimuli with code-switches are respectively constructed through the various splicing processes.

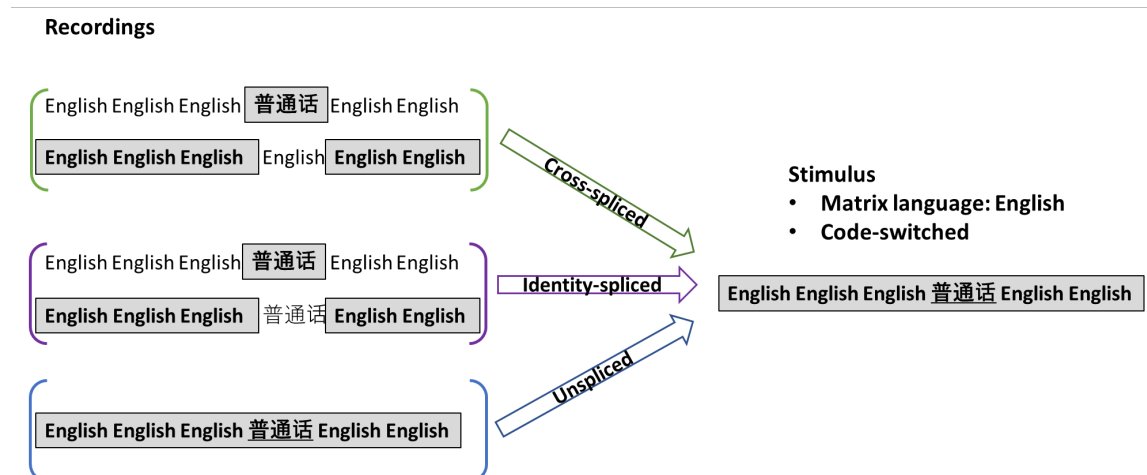
Unilingual stimuli were also constructed via identity-splicing, with the target word taken from a unilingual recording and combined with the frame from another unilingual recording of the same sentence. Identity-spliced unilingual stimuli control for any effects of the identity-splicing process. Figure 17 and Figure 18 illustrate how Mandarin and English sentence stimuli with code-switches are respectively constructed through the various splicing processes.

The unspliced stimuli that are not phonetically manipulated in any way and used as naturally recorded are the stimuli in which code-switched target words are preceded by anticipatory phonetic cues and unilingual target words are produced in a natural context as well.

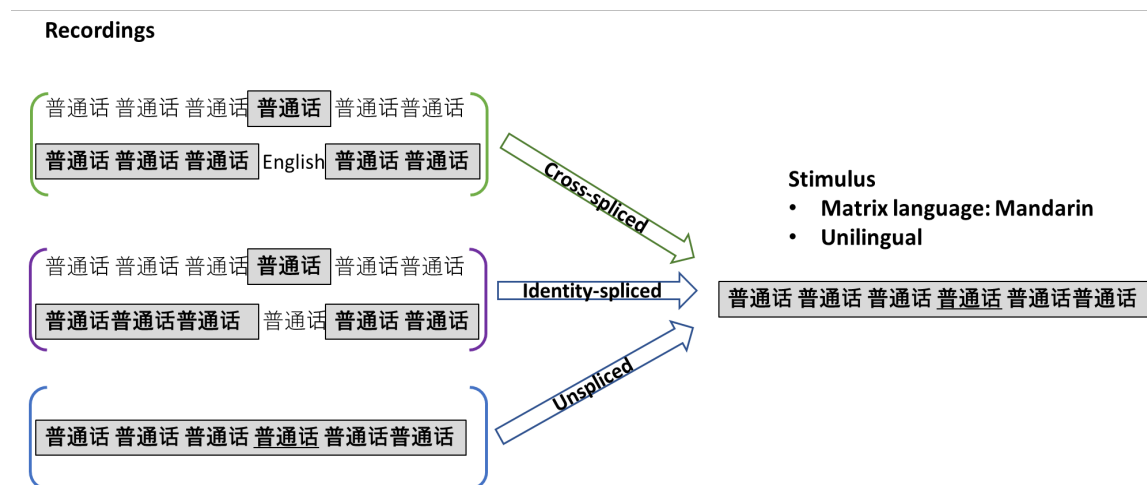
Given these manipulations, I hypothesize that there will be the fewest looks toward on trials with cross-spliced code-switched stimuli, since the code-switched target words will not be preceded by phonetic cues. In general, on trials with cross-spliced stimuli, there should be fewer looks to the target, due to the incongruent cues (no switch cues before code-switch; switch cues before unilingual target). Looks to the target on identity-spliced trials compared to unspliced trials might be similar, unless identity-splicing results in stimuli that are phonetically unnatural in a perceptible way.



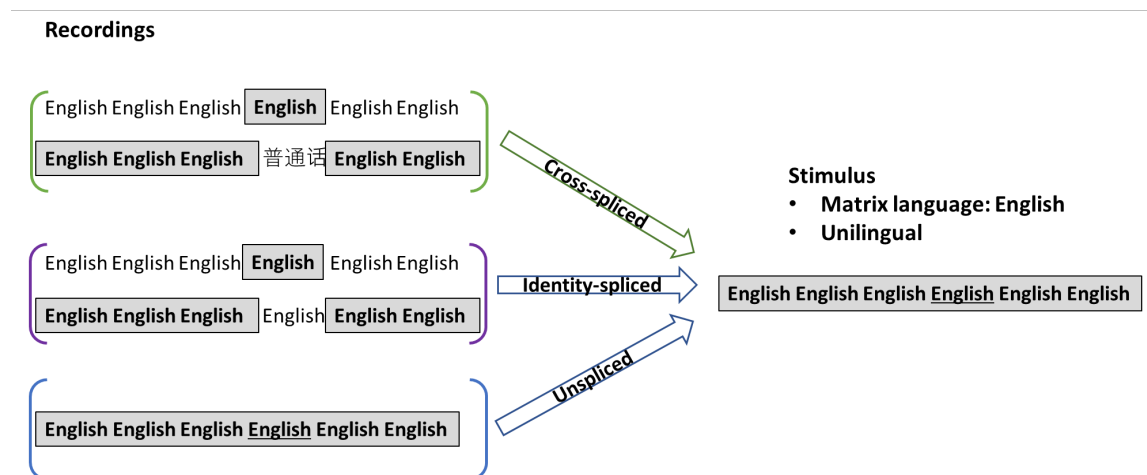
**Figure 15.** Constructing Mandarin sentence stimuli with code-switches.



**Figure 16.** Constructing English sentence stimuli with code-switches.



**Figure 17.** Constructing unilingual Mandarin sentence stimuli.



**Figure 18.** Constructing unilingual English sentence stimuli.

Since the unspliced, cross-spliced, and identity-spliced versions of each sentence differed only in the splicing manipulation, three experimental lists were created for counterbalancing so that participants would not hear the same sentence in multiple conditions. Each list contained 24 or 25 unspliced, cross-spliced, and identity-spliced stimuli, so that participants would hear all stimulus types but only one version of each sentence. Trials were presented blocked by matrix language, but in random order for all lists and all participants within each block. Table 11 shows the number of each type of stimulus presented in each experimental list.

	<b>List 1</b>	<b>List 2</b>	<b>List 3</b>
<b>Unspliced</b>	25	25	24
<b>Identity-spliced</b>	25	24	25
<b>Cross-spliced</b>	24	25	25

**Table 11.** Experimental lists, with number of stimuli from each condition.

### *Procedure*

Data collection took place in the PhonLab in the Department of Linguistics at the University of California, Berkeley. Participants first completed a familiarization task, during which they familiarized themselves with the 148 pictures that they would see in the main experiment.

The main experiment was a visual world paradigm eye tracking experiment. On each trial, four pictures were presented, with one picture in each quadrant of the screen. The four pictures corresponded to the target noun, a Mandarin competitor, an English competitor, and a distractor. Competitors had similar phonological onsets as the target, while the distractor did not share an onset with the other three words. The locations of the four pictures were randomized on each trial so that each picture type would not consistently occur in the same quadrant of the screen.

The eye-tracking participant was calibrated twice with two separate nine-point calibration screens before the experiment began. The calibration process was repeated until the average calibration error was 0.25 or under. Then they were presented English instructions on the computer screen, informing them that they would hear Mandarin and English throughout the experiment. Instructions stated that they might hear both languages in the same sentence, and that prior to each trial, they should fixate on a center fixation dot. During the trial, they would see four pictures, and hear a sentence through headphones. Their task was to identify the object mentioned in the sentence, and to look toward it. They were informed that the object might be named in Mandarin or English, and to look toward it regardless of language. An experimenter was present to reiterate and clarify instructions, and to answer questions.

Participants completed the eye tracking experiment in a sound-attenuated booth, and were presented auditory stimuli via AKG K240 headphones. Participants were seated in front of a 22-inch screen with a visual world display that had a resolution of 512 x 384 pixels. Between trials, a center fixation dot functioned to correct eye gaze drift. Each trial lasted 3500ms, with 1000ms between trials. The experiment was blocked by matrix language. Odd-numbered subjects heard the English block first, while even-numbered subjects heard the Mandarin block first. Within each experimental block, presentation of unilingual and code-switched trials was randomized. The experiment lasted approximately 10 minutes.

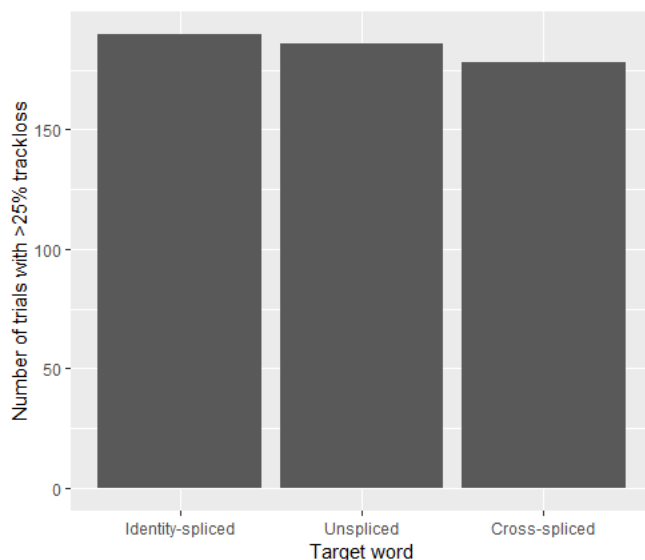
Following the experiment, participants completed the Bilingual Language Profile and the code-switching questionnaire. The entire study lasted approximately 50 minutes, and participants were compensated \$5 for the completion of each experiment or questionnaire, for a total of \$15.

### *Data analysis*

Six participants' data were excluded from analysis due to computer display errors, drift correction errors, high calibration errors, or incomplete data. There were therefore 48 participants, with 74 trials per participant, and 102 observations per trial, resulting in a total of 362,304 observations. Observations that occurred out of range of the visual display were excluded, resulting in the removal of 4961 observations (1.37% of the total).

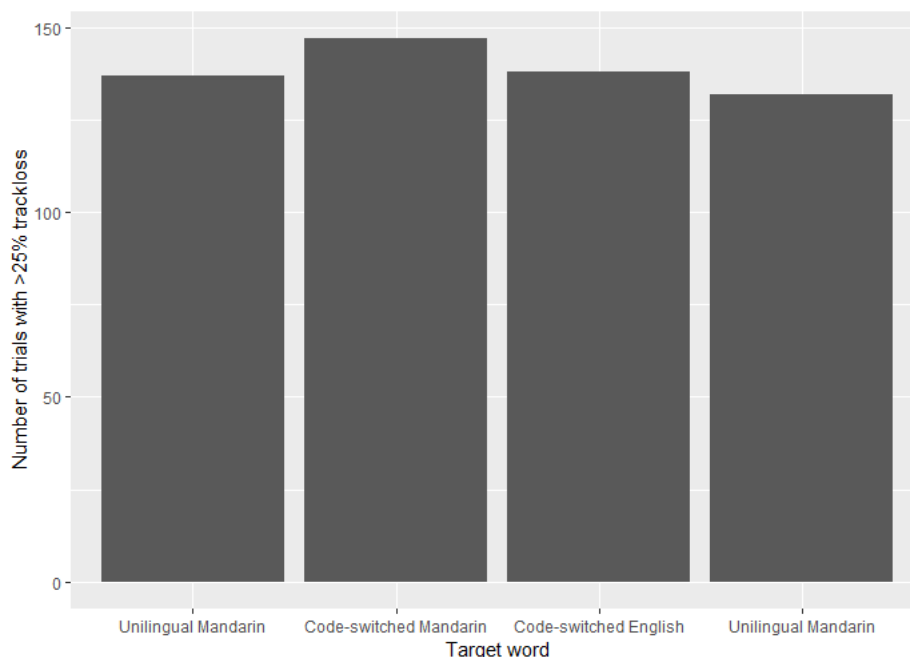
For a given participant, any trials where the visual display involved a picture corresponding to a noun that the participant marked as unfamiliar during the familiarization task were excluded, resulting in the removal of 6,512 observations (1.8% of the total).

Observations where the eye-tracker failed to record gaze location were marked as trackloss. The eyetrackingR package (Dink & Ferguson, 2015) was used to exclude any trials with more than 25% trackloss. 554 trials were excluded in this manner, and these trials were relatively evenly distributed across different conditions (Figure 19 and Figure 20). On average, 92% of trials (SD = .05) were retained for each participant after trackloss exclusion, so that a total of 297,259 observations remained.



**Figure 19.** Distribution of 554 trials that were removed due to over 25% trackloss, by Splice.





**Figure 20.** Distribution of 554 trials that were removed due to over 25% trackloss, by target word.

Areas of interest were defined as the four quadrants of the visual display, excluding 32 px wide vertical and horizontal margins in the center of the screen surrounding the location of the fixation dot and between quadrants. 8 observations were excluded in this manner.

Looks falling within the quadrant of each type of picture in the visual world display (English or Mandarin target, English phonological cohort competitor, Mandarin phonological cohort competitor, distractor) were counted as fixations to that picture. Average proportion of fixations for a condition was calculated by dividing the sum of fixations towards a type of picture across all participants and trials in that condition by the total number of trials in that condition. The average proportion of fixations to target images was the dependent measure in the analyses.

The main analysis focused on the time window from 200 ms after the target word onset to 1500 ms, which is when target fixations plateaued. Following Mirman (2014), growth curve analysis with third-order orthogonal polynomial time terms was used to model the time course of fixations to the picture corresponding to the target word. Separate analyses were conducted for trials with Mandarin sentence stimuli and trials with English sentence stimuli.

Including orthogonal polynomials in the growth curve analysis accounted for the shape of the time course of fixations, which upon visual inspection of the raw time course data was determined to be cubic. The random effects structure for the model included by-subject, by-target, and subject-by-splicing condition random slopes (Baayen et al., 2008).

Assessment of best-fitting models for the data began with a baseline model with gradually added variables to produce multiple models increasing in complexity. A likelihood ratio test, implemented with the R `anova()` function, was used to compare the baseline model with the more complex models, assessing the best-fitting model with a combination of log likelihood, Akaike information criterion (AIC), and Bayesian information criterion (BIC). Alpha levels of 0.05 were used to evaluate the significance of each predictor. All fixed and random variables interacted with linear, quadratic, and cubic orthogonal polynomials.

Analyses of looks to targets separately considered looks to targets in English sentences and targets in Mandarin sentences, so that there was a separate model for each sentence language. Each model included an interaction between Switch (whether the target word was code-switched or not), Splice (whether the target was unspliced, cross-spliced, or identity-spliced), and BLP (the subject's language dominance score on the BLP), along with linear, quadratic, and cubic orthogonal polynomials to capture the shape of the curve. The reference levels for these fixed effects were no code-switch, unspliced, and balanced bilingual (BLP score of 0). Full random effects are included, with random slopes for subject, an interaction between subject and Splice, and target. Alpha levels of 0.05 were used to evaluate the significance of each predictor.

## Results

I hypothesized that dominant language, frequency of switch direction (Mandarin-to-English vs. English-to-Mandarin), and phonetic cuing would affect the auditory comprehension of Mandarin and English code-switches, potentially resulting in an asymmetric switch cost. We expect to see switch costs in Mandarin-English code-switching, with a significant effect of Switch indicating that there were fewer looks to code-switches than unilingual target words for a particular sentence language.

If dominant language affects switch cost in recognition similarly as in production, then code-switches in the participant's dominant language will have a greater processing cost. For example, a Mandarin-dominant bilingual would be slower to recognize a Mandarin code-switch than an English code-switch. In terms of eye-tracking results, we might see an interaction between Switch and Dominance, such that there are fewer looks to code-switches when they are in the participant's dominant language. On the other hand, if dominant language affects switch cost differently in recognition, such as the result in Experiment 2, then code-switches in the participant's dominant language would be less costly than those in the non-dominant language. For example, a Mandarin-dominant bilingual would be faster to recognize a Mandarin code-switch than an English code-switch. This would also be an interaction between Switch and Dominance, with more looks to code-switches when they are in the participant's dominant language.

If frequency of switch direction affects switch cost, indicating that code-switching experience plays a role in recognition, then infrequent code-switches would incur a greater processing cost than frequent code-switches. Since the results analyze looks to targets in English sentences and Mandarin sentences separately, we might see several different patterns of results. One is that Switch is a significant effect in both analyses, but with a larger estimate for English code-switches in Mandarin sentences (the frequent switch type) than for Mandarin code-switches in English sentences (the infrequent switch type). Another is that Switch will only be a significant effect in the English sentence analysis, so that only infrequent Mandarin code-switches in English sentences incur a switch cost, whereas in Mandarin sentences, there might be no difference between looks to images corresponding to unilingual Mandarin words compared to code-switched English words.

If phonetic cuing affects switch cost, such that listeners can anticipate upcoming code-switches, then uncued code-switches would incur a greater processing cost than cued code-switches. We would therefore see a significant interaction between Switch and Splice, with more looks to unspliced code-switched targets, which retain anticipatory phonetic cues, than cross-

spliced code-switched targets, which are code-switches spliced into unilingual frames to withhold anticipatory phonetic cues. Identity-spliced code-switched targets might pattern somewhere in between unspliced and cross-spliced code-switched targets, since the frame is phonetically consistent but still the result of manipulation. This phonetic cuing is expected to take the form of some phonetic pattern unique to code-switches, but we might also see phonetic patterns that are localized to the specific target word, regardless of language or switch, such as anticipatory coarticulation. The splicing manipulation is expected to show an effect of phonetic cuing, whether switch-unique or target-unique.

We first examine the analysis for looks to targets in English sentences, going through each of these hypotheses, before turning to a similar analysis for looks to targets in Mandarin sentences. The reference levels were no switch or unilingual for Switch, unspliced for Splice, and balanced bilingual for Dominance (BLP language dominance score of 0 on -218 to 218 scale).

### ***Looks to targets: English sentences***

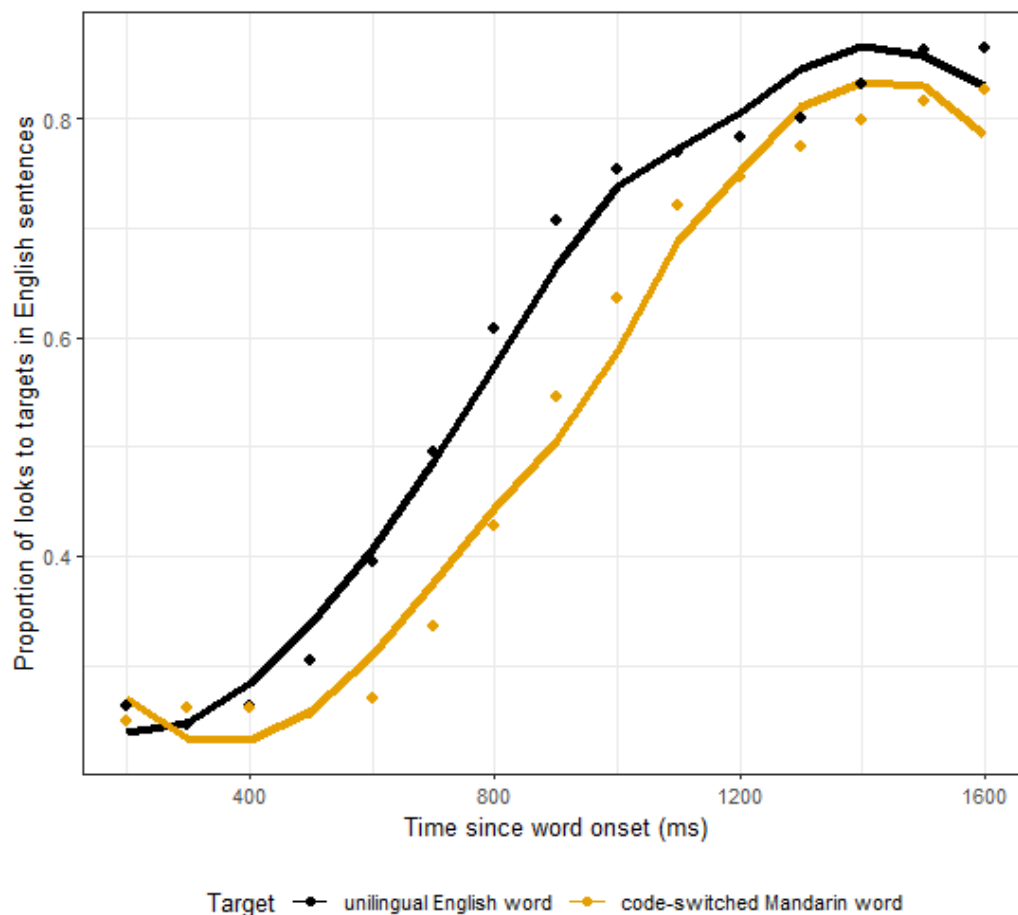
The model for looks to images corresponding to targets in English sentences can be found in Table 12. We see a switch cost in English sentences, with a significant effect of Switch indicating overall fewer looks to code-switched Mandarin targets compared to unilingual English targets ( $Est = -.1, SE = .04, p = .01$ ). Thus, in English sentences, code-switched Mandarin words incur a processing cost compared to unilingual English words (Figure 21). This result is as hypothesized, both matching the result in Experiment 2 and showing that infrequent code-switches incur a switch cost, though comparison to frequent code-switches awaits the following analysis of Mandarin sentences.

	$\beta$	Std. Error	$t$ value	Pr(>  $t$  )
1. (Intercept)	0.6421	0.0303	21.180	<2e-16 ***
2. Linear polynomial	0.9779	0.0791	12.361	<2e-16 ***
3. Quadratic polynomial	-0.1060	0.0498	-2.133	0.03628 *
4. Cubic polynomial	-0.2064	0.0398	-5.181	1.04e-06 ***
5. Switch – Yes	-0.0978	0.0376	-2.604	0.01362 *
6. Spliced – Identity	-0.0379	0.0229	-1.659	0.09968 .
7. Spliced – Cross	-0.0473	0.0229	-2.067	0.04078 *
8. BLP	0.0132	0.0181	0.726	0.46874
9. Lin:SwitchY	-0.0076	0.0988	-0.077	0.93936
10. Quad:SwitchY	0.0480	0.0675	0.711	0.47955
11. Cub:SwitchY	-0.0653	0.0555	-1.176	0.24233
12. Lin:SpliceI	-0.0373	0.0704	-0.479	0.63237
13. Lin:SpliceX	0.0023	0.0703	0.033	0.97372
14. Quad:SpliceI	-0.0237	0.0470	-0.504	0.61445
15. Quad:SpliceX	-0.0379	0.0470	-0.806	0.42081
16. Cub:SpliceI	0.0309	0.0465	0.664	0.50676
17. Cub:SpliceX	0.0209	0.0464	0.450	0.65292
18. SwitchY:SpliceI	0.0320	0.0173	1.847	0.06471 .
19. SwitchY:SpliceX	0.0414	0.0169	2.458	0.01399 *
20. Lin:BLP	0.0632	0.0527	1.199	0.23218
21. Quad:BLP	0.0121	0.0367	0.329	0.74255
22. Cub:BLP	-0.0179	0.0331	-0.541	0.58842
23. SwitchY:BLP	-0.0024	0.0123	-0.198	0.84299
24. SpliceI:BLP	0.0025	0.0229	0.108	0.91391
25. SpliceX:BLP	0.0106	0.0229	0.464	0.64333
26. Lin:SwitchY:SpliceI	-0.0673	0.0687	-0.981	0.32677
27. Lin:SwitchY:SpliceX	-0.0101	0.0667	-1.510	0.13111
28. Quad:SwitchY:SpliceI	0.0124	0.0673	1.849	0.06447
29. Quad:SwitchY:SpliceX	0.0880	0.0651	1.351	0.17661
30. Cub:SwitchY:SpliceI	0.0217	0.0648	0.334	0.73818
31. Cub:SwitchY:SpliceX	0.0288	0.0634	0.612	0.54074
32. Lin:SwitchY:BLP	-0.1058	0.0484	-2.184	0.02901 *
33. Quad:SwitchY:BLP	0.0337	0.0468	0.719	0.47222
34. Cub:SwitchY:BLP	0.0713	0.0455	1.566	0.11730
35. Lin:SpliceI:BLP	-0.0499	0.0705	-0.708	0.48034
36. Lin:SpliceX:BLP	-0.1214	0.0702	-1.730	0.08590 .
37. Quad:SpliceI:BLP	-0.0476	0.0469	-1.016	0.31078
38. Quad:SpliceX:BLP	-0.0980	0.0465	-2.107	0.03618 *
39. Cub:SpliceI:BLP	0.0039	0.0464	0.085	0.93225
40. Cub:SpliceX:BLP	0.0569	0.0461	1.235	0.21749
41. SwitchY:SpliceI:BLP	-0.0136	0.0172	-0.789	0.43014
42. SwitchY:SpliceX:BLP	-0.0470	0.0168	-2.796	0.00517 **
43. Lin:SwitchY:SpliceI:BLP	-0.0244	0.0681	-0.358	0.72009

44. Lin:SwitchY:SpliceX:BLP	0.0792	0.0666	1.190	0.23397
45. Quad:SwitchY:SpliceI:BLP	-0.0091	0.0665	-0.137	0.89122
46. Quad:SwitchY:SpliceX:BLP	0.0131	0.0647	2.023	0.04313 *
47. Cub:SwitchY:SpliceI:BLP	-0.0538	0.0644	-0.836	0.40337
48. Cub:SwitchY:SpliceX:BLP	-0.0644	0.0631	-1.021	0.30725

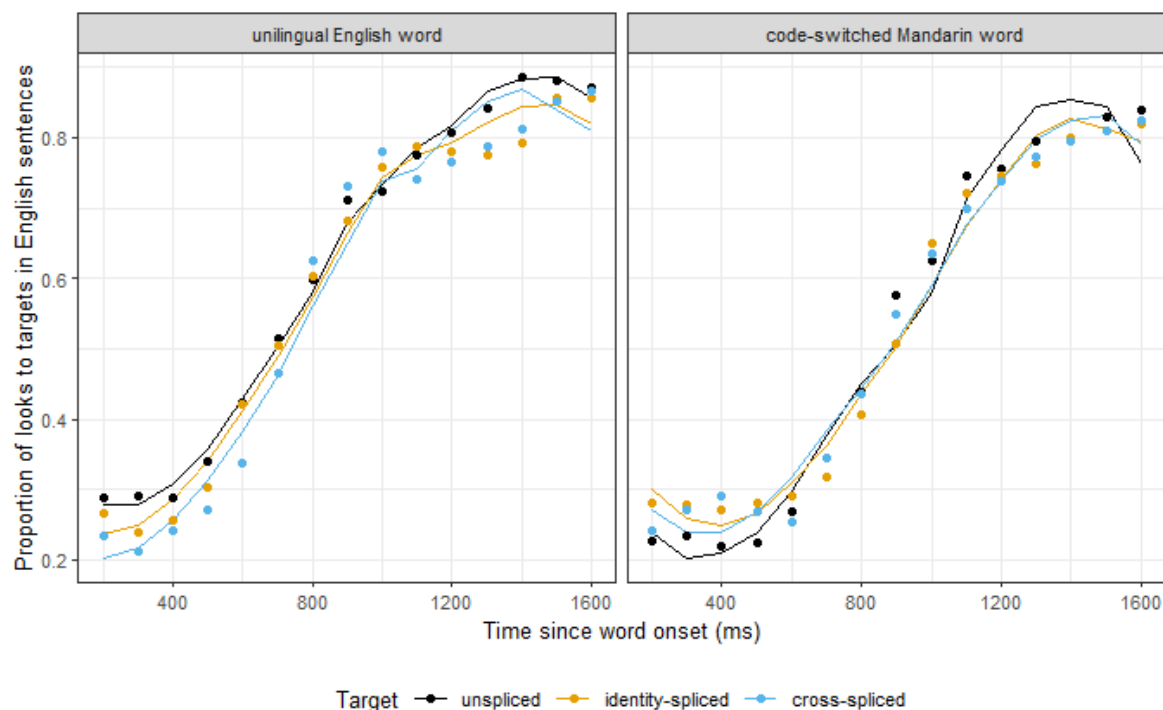
Groups	Name	Variance	Std.Dev.	Corr.		
Subject:Splice	(Intercept)	0.009207	0.09596			
	ot1	0.068913	0.26251	0.40		
	ot2	0.007601	0.08718	-0.35	-0.33	
	ot3	0.007845	0.08857	-0.54	-0.99	0.33
Subject	(Intercept)	0.003286	0.05733			
	ot1	0.016181	0.12721	0.71		
	ot2	0.014418	0.12007	-0.86	-0.26	
	ot3	0.002809	0.05300	-0.67	-1.00	0.21
Target	(Intercept)	0.010167	0.10083			
	ot1	0.055005	0.23453	0.74		
	ot2	0.019750	0.14053	-0.89	-0.62	
	ot3	0.006779	0.08234	-0.69	-0.92	0.40
Residual		0.156049	0.39503			

**Table 12.** Fixed and random effects of growth curve analysis of Experiment 3 eye-tracking data: Looks to targets in English sentences, as a function of Switch, Splice, and BLP (Dominance, with positive BLP scores indicating English-dominance and negative Mandarin-dominance).



**Figure 21.** Empirical data (points) and model fit (lines) for proportion of looks to targets in English sentences, by Switch, across all participants and trials.

The interaction between Switch and Splice (cross-splice) was significant: When targets were code-switched, there were more looks to cross-spliced targets compared to unspliced targets ( $Est = .04$ ,  $SE = .02$ ,  $p = .01$ ). This is unexpected, showing that withholding phonetic cues is not only not detrimental in the recognition of code-switched targets, but actually advantageous in this experiment, contrary to the hypothesis and to the results of Experiment 2. Perhaps cross-splicing resulted in some perceptible phonetic weirdness that listeners were able to use as a cue to code-switches, although a qualitative evaluation of spliced stimuli after manipulation did not suggest any such phonetic consequences. We will return to this result in the Acoustic Analysis section, where I discuss the production patterns of the bilingual speaker for this experiment, who is a separate speaker from the one who recorded Experiment 2 stimuli.

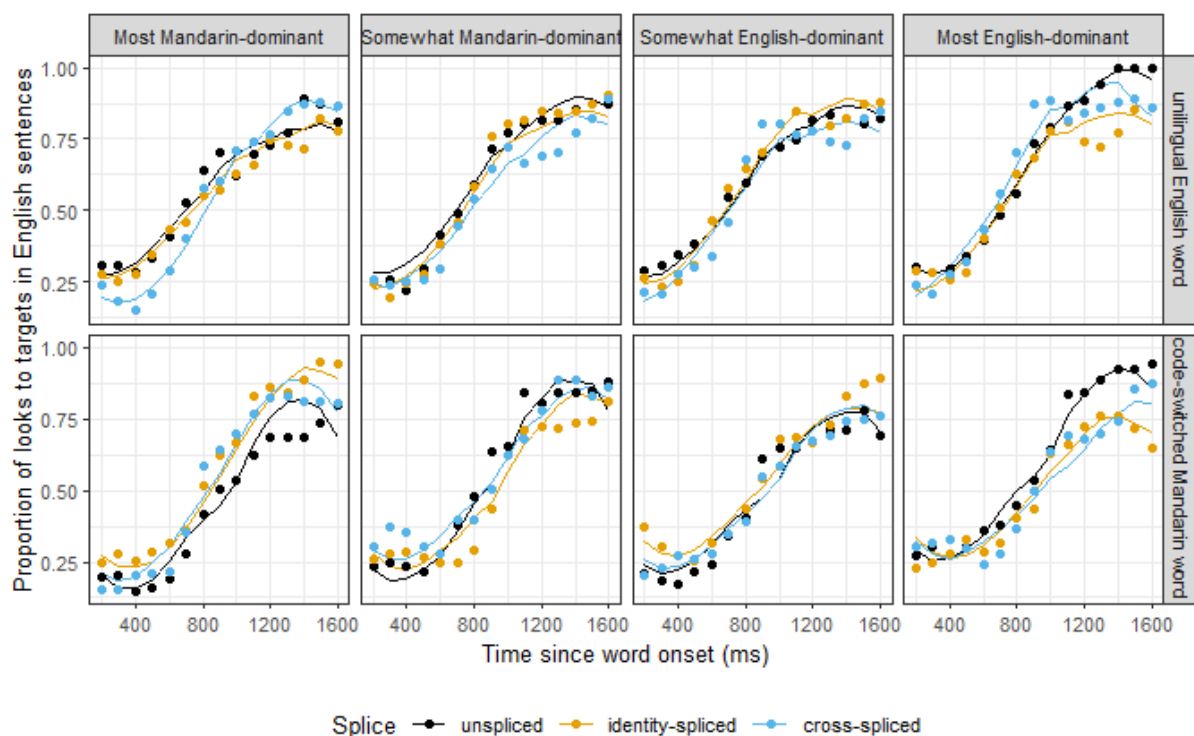


**Figure 22.** Empirical data (points) and model fit (lines) for proportion of looks to targets in English sentences, by Switch and Splice, across all participants and trials.

There were also other interesting effects that reached or approached significance. The near-significant interaction between Switch and Splice (identity-splice) indicates more looks to identity-spliced than unspliced code-switched targets (Table 12; row 18), which further indicates some interesting advantage of being spliced for code-switched Mandarin words in English sentences. The right panel of Figure 22, which plots Switch against Splice, illustrates that this splicing advantage might be specific to the early window after the target onset. Splice (cross-splice) was also significant for unilingual targets, with fewer looks to cross-spliced than unspliced unilingual English targets (Table 12; row 7), and near-significant for identity-splicing, with fewer looks to identity-spliced than unspliced unilingual English targets (Table 12; row 6). Interestingly, unilingual targets have the hypothesized effect of splicing but code-switched targets do not.

Finally, while there was no significant interaction between Switch and Dominance (Table 12; row 23), the three-way interaction between Switch, Splice (cross-spliced), and Dominance was significant, with fewer looks toward cross-spliced code-switched Mandarin targets when the participant was more English-dominant (Table 12; row 42). Language dominance doesn't seem to affect the recognition of code-switching in general, but when cues to the code-switch are withheld through cross-splicing, being dominant in the code-switch language is advantageous, which is why English-dominant listeners had fewer looks toward cross-spliced Mandarin code-switched targets compared to Mandarin-dominant listeners (Figure 23). There were additionally significant interactions with various orthogonal polynomials with consequences for the rate of looks to targets: the rate of looks to code-switched targets was slower when the participant scored as more English-dominant (Table 12; row 32); the rate of looks to cross-spliced targets was slower when the participant scored as more English-dominant (Table 12; row 38); the rate of

looks to cross-spliced code-switched targets was slower when the participant scored as more English-dominant (Table 12; row 46).



**Figure 23.** Empirical data (points) and model fit (lines) for proportion of looks to targets in English sentences, by Switch, Splice, and Dominance, across all participants and trials.

#### *Post-hoc analysis: Identity-splicing vs. cross-splicing*

A post-hoc analysis removed unspliced tokens to directly compare identity-spliced and cross-spliced tokens and determine whether the two types of splicing differently affected looks to the target. The model otherwise had the same fixed and random effects as the previous model. Identity-splicing did not produce any significant difference in looks to unilingual or code-switched targets in English sentences compared to cross-splicing ( $Est = -.009$ ,  $SE = .02$ ,  $p = .69$ ;  $Est = .006$ ,  $SE = .02$ ,  $p = .72$ ). Switch was near-significant for unilingual targets though ( $Est = -.07$ ,  $SE = .04$ ,  $p = .05$ ), with fewer looks to identity-spliced than cross-spliced targets.

Therefore, there was no difference between the effects of identity-splicing and cross-splicing on looks to targets. Overall, there were fewer looks to identity- and cross-spliced unilingual targets than unspliced unilingual targets, but as indicated in the original analysis, there were more looks to identity- and cross-spliced code-switched targets than unspliced code-switched targets.

#### *Post-hoc analysis: No splicing vs. any splicing*

A further post-hoc analysis combined identity-spliced and cross-spliced tokens into one group of spliced tokens, to determine whether there was any general difference between being spliced or not. Other than that, the model had the same random and fixed effects as the original model. For unilingual targets, there was a significant difference between being unspliced or



spliced, with fewer looks to spliced unilingual targets ( $Est = -.04, SE = .02, p = .03$ ). Switch was significant, with fewer looks to unspliced targets when they were code-switched ( $Est = -.1, SE = .04, p = .01$ ). The interaction between Switch and Splice was significant, with more looks to spliced than unspliced code-switched targets ( $Est = .04, SE = .02, p = .01$ ). The three-way interaction between Switch, Splice, and Dominance was also significant, with fewer looks to spliced code-switches when the participant was more English-dominant than Mandarin-dominant ( $Est = -.04, SE = .01, p = .01$ ).

This post-hoc analysis indicates that splicing had opposite effects on unilingual and code-switched targets. For unilingual targets, there were more looks to unspliced targets. For code-switched targets, there were more looks to spliced targets.

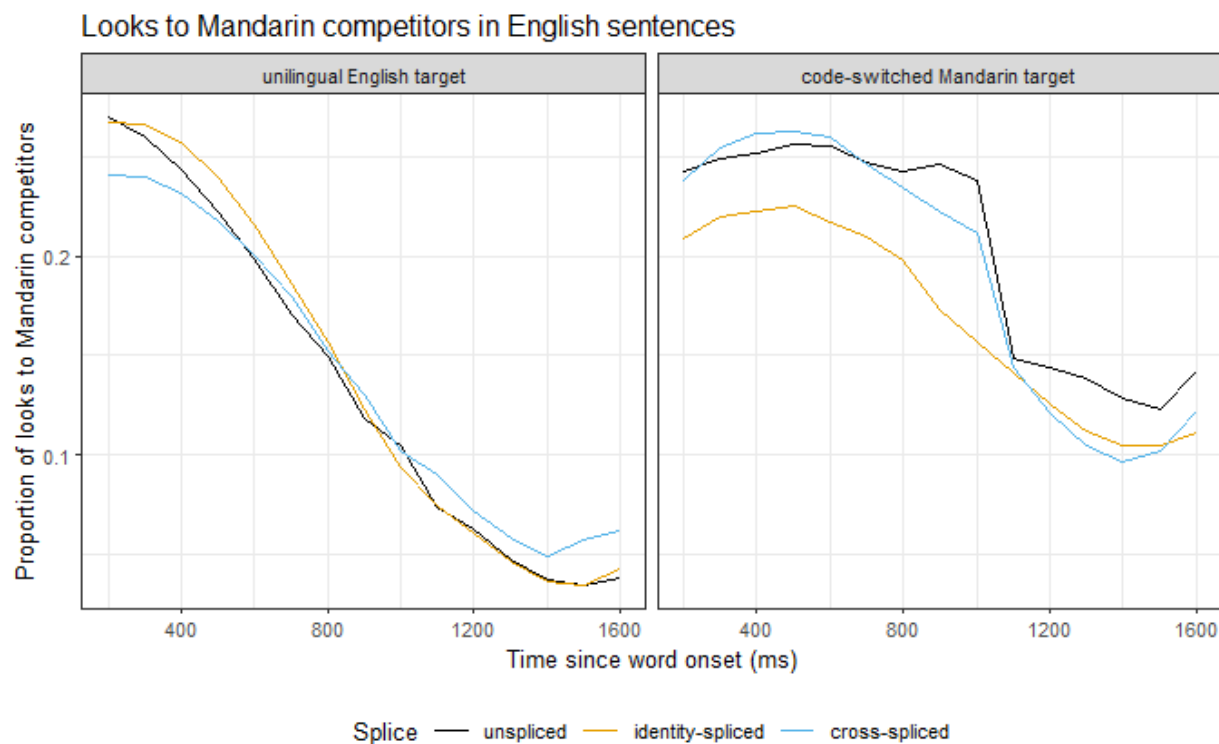
Both post-hoc analyses confirm that splicing – whether identity-splicing or cross-splicing – had an unexpected effect such that spliced code-switched targets in English sentences were easier to recognize. It is possible that the splicing process in general, even though done carefully, resulted in some audible difference that participants picked up on and attributed to an upcoming code-switch.

#### *Looks to Mandarin competitors in English sentences*

A separate analysis analyzed looks to Mandarin competitors in English sentences, with a three-way interaction between Switch, Splice, and Dominance, and up to third-order orthogonal polynomials (Appendix G). The random slopes were by-subject, by-target, and subject-by-splicing. If there were anticipatory phonetic cues biasing listeners to expect Mandarin words in English sentences, then we might see similar significant effects to the looks to targets analysis. Specifically, we might see significant effects for Switch, the interaction between Switch and Splice (cross-spliced), and the interaction between Switch, Splice (cross-spliced), and Dominance. In the looks to targets analysis, recall that there were (a) fewer looks to Mandarin code-switches, (b) more looks to cross-spliced Mandarin code-switches, and (c) fewer looks to cross-spliced code-switches by English-dominant listeners.

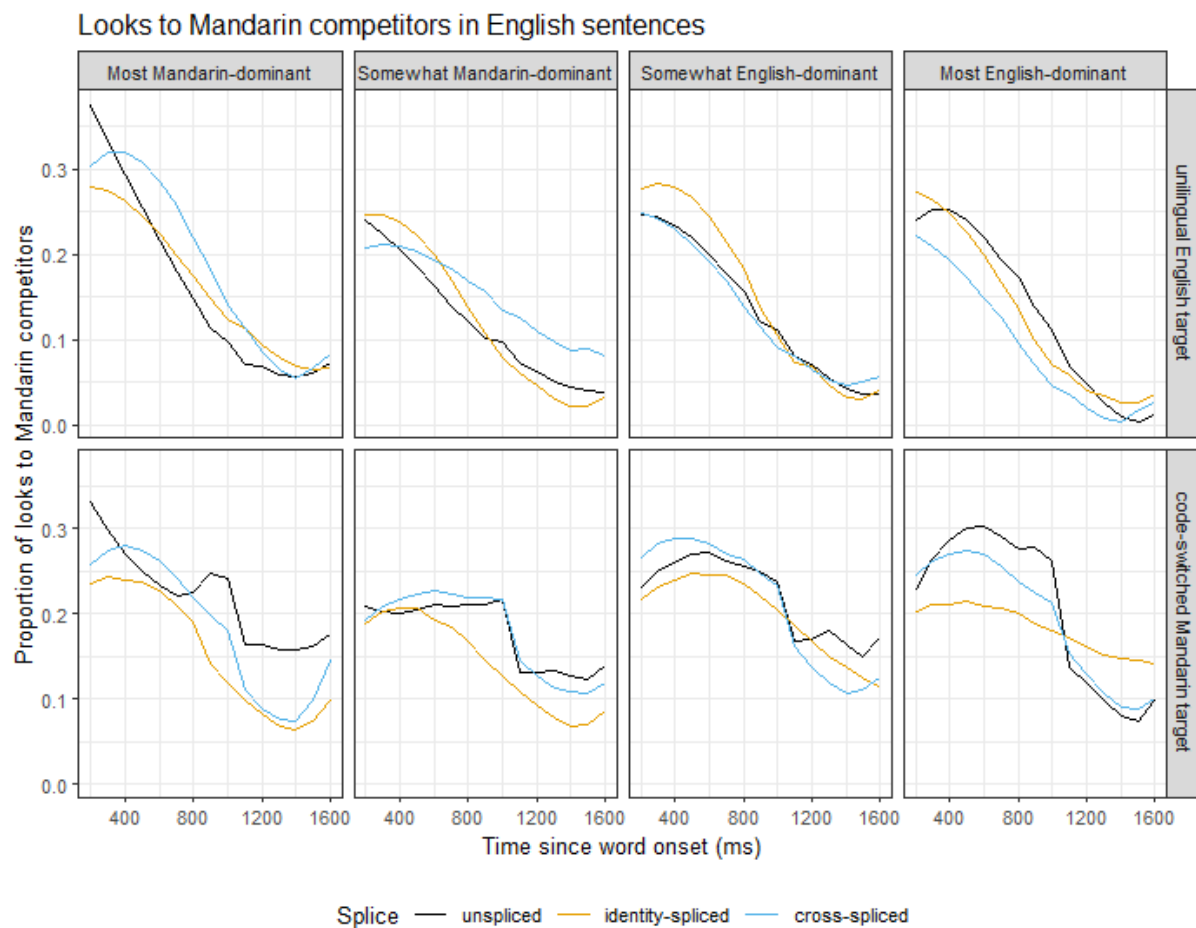
There was a significant effect of Switch: more looks to Mandarin competitors when targets were unspliced Mandarin code-switches compared to when targets were unilingual English words (Figure 24;  $Est = .07, SE = .03, p = .03$ ). This suggests that naturally produced Mandarin code-switches seem to be characterized by some sort of phonetic cue that directs listeners toward expecting to hear Mandarin instead of English, which results in more looks toward Mandarin competitors on switch trials.

However, the interaction between Switch and Splice (cross-spliced) was not significant (Figure 23;  $Est = -.006, SE = .01, p = .65$ ), indicating no difference between looks to Mandarin competitors when the target was either an unspliced or cross-spliced Mandarin code-switch. Even though there were more looks to cross-spliced compared to unspliced Mandarin code-switched targets, this did not carry over to Mandarin competitors, suggesting that the cross-splicing process did not seem to bias listeners toward expecting a Mandarin word in general. The advantage of cross-splicing for Mandarin targets remains to be discussed.



**Figure 24.** Empirical data (points) and model fit (lines) for proportion of looks to Mandarin competitors in English sentences, by Switch, across all participants and trials

The three-way interaction between Switch, Splice (cross-spliced), and Dominance was significant, however: more looks to Mandarin competitors when the target was a cross-spliced code-switch and the listener was more English-dominant (Figure 25;  $Est = .03$ ,  $SE = .01$ ,  $p = .05$ ). This is an interesting result, especially alongside the finding that English-dominant listeners were worse than Mandarin-dominant listeners at identifying cross-spliced Mandarin code-switches. Given that all of the competitors shared a phonological onset with the target, and some were even segmental homophones differing only in tone, it seems plausible that English-dominant listeners, being less Mandarin-dominant, were more easily confused by the Mandarin competitors. Some of these Mandarin target and competitor pairs are shown in Appendix I, while other significant effects can be found in Appendix G.



**Figure 25.** Empirical data (points) and model fit (lines) for proportion of looks to Mandarin competitors in English sentences, by Switch, Splice, and Dominance, across all participants and trials.

### ***Looks to targets: Mandarin sentences***

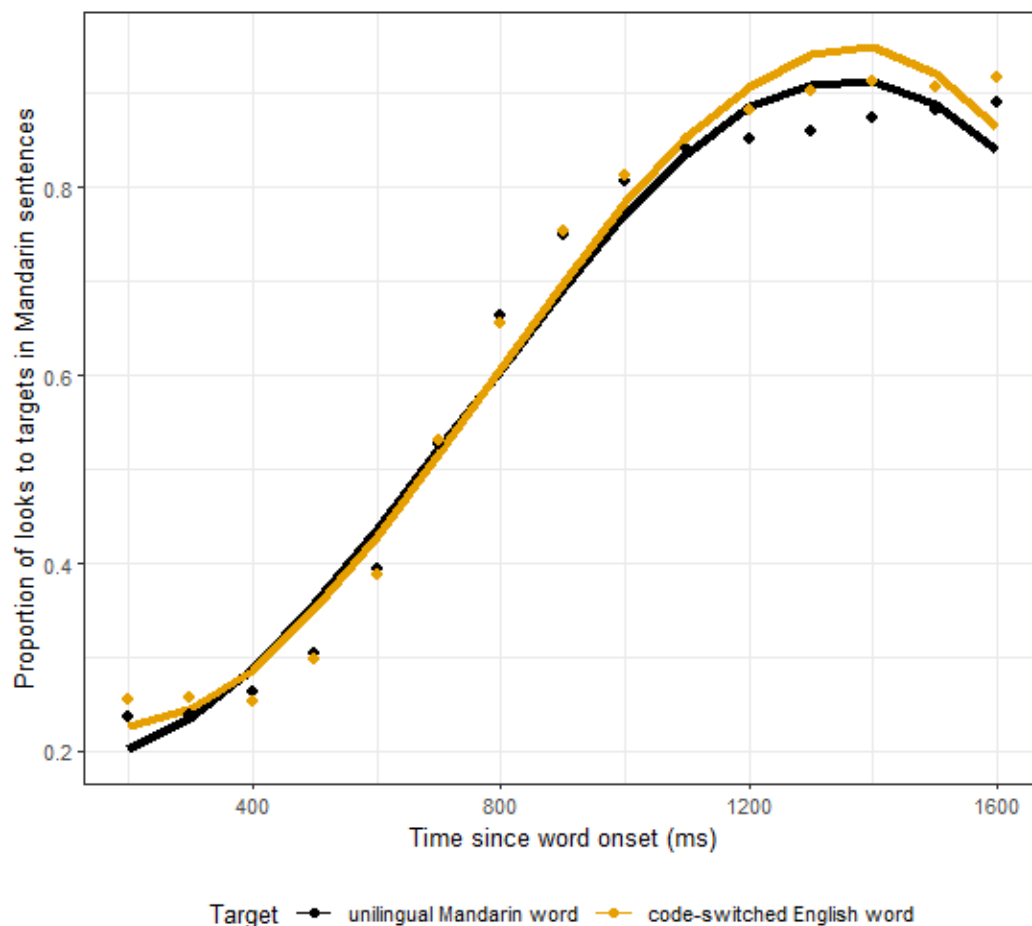
The model for looks to targets in Mandarin sentences (Table 13) was identical to the analysis of trials with English sentence stimuli, in terms of fixed and random effects. There was no switch cost, with no difference between looks to unilingual Mandarin words and code-switched English words ( $Est = .002$ ,  $SE = .03$ ,  $p = .94$ ; Figure 26). Taken with the switch cost found in English sentences, these results are consistent with the hypothesis that infrequent code-switches (Mandarin words in English sentences) would incur a greater processing cost than frequent code-switches (English words in Mandarin sentences).

	$\beta$	Std. Error	$t$ value	Pr(>  $t$  )
1. (Intercept)	0.6331	0.0262	24.171	<2e-16 ***
2. Linear polynomial	0.9481	0.0601	15.775	<2e-16 ***
3. Quadratic polynomial	-0.2113	0.0456	-4.630	1.01e-05 ***
4. Cubic polynomial	-0.1790	0.0345	-5.186	8.25e-07 ***
5. Switch – Yes	0.0024	0.0326	0.074	0.94116
6. Spliced – Identity	-0.0012	0.0151	-0.081	0.93532
7. Spliced – Cross	-0.0111	0.0150	-0.741	0.46007
8. BLP	-0.0265	0.0137	-1.937	0.05498 .
9. Lin:SwitchY	0.0554	0.0730	0.758	0.45158
10. Quad:SwitchY	0.0266	0.0543	0.490	0.62562
11. Cub:SwitchY	-0.0169	0.0458	-0.368	0.71357
12. Lin:SpliceI	0.0281	0.0491	0.572	0.56809
13. Lin:SpliceX	0.0387	0.0490	0.790	0.43045
14. Quad:SpliceI	0.0002	0.0399	0.006	0.99536
15. Quad:SpliceX	-0.0330	0.0397	-0.832	0.40595
16. Cub:SpliceI	0.0207	0.0375	0.553	0.58044
17. Cub:SpliceX	-0.0080	0.0374	-0.213	0.83146
18. SwitchY:SpliceI	0.0225	0.0129	1.742	0.08150 .
19. SwitchY:SpliceX	0.0073	0.0128	0.571	0.56834
20. Lin:BLP	0.0130	0.0397	0.328	0.74330
21. Quad:BLP	0.0152	0.0354	0.428	0.66906
22. Cub:BLP	-0.0239	0.0279	-0.855	0.39281
23. SwitchY:BLP	0.0760	0.0091	8.362	<2e-16 ***
24. SpliceI:BLP	0.0154	0.0152	1.014	0.31228
25. SpliceX:BLP	0.0009	0.0152	0.061	0.95177
26. Lin:SwitchY:SpliceI	-0.0544	0.0509	-1.069	0.28522
27. Lin:SwitchY:SpliceX	-0.0073	0.0505	-0.145	0.88505
28. Quad:SwitchY:SpliceI	-0.0364	0.0505	-0.721	0.47121
29. Quad:SwitchY:SpliceX	0.0432	0.0502	0.862	0.38897
30. Cub:SwitchY:SpliceI	-0.0259	0.0502	-0.516	0.60612
31. Cub:SwitchY:SpliceX	-0.0126	0.0499	-0.252	0.80095
32. Lin:SwitchY:BLP	0.0344	0.0360	0.956	0.33898
33. Quad:SwitchY:BLP	-0.0807	0.0355	-2.273	0.02307 *
34. Cub:SwitchY:BLP	0.0413	0.0354	1.167	0.24314
35. Lin:SpliceI:BLP	-0.0177	0.0494	-0.358	0.72081
36. Lin:SpliceX:BLP	-0.0093	0.0495	-0.188	0.85125
37. Quad:SpliceI:BLP	0.0029	0.0399	0.074	0.94144
38. Quad:SpliceX:BLP	-0.0285	0.0400	-0.712	0.47698
39. Cub:SpliceI:BLP	0.0658	0.0375	1.756	0.07965 .
40. Cub:SpliceX:BLP	0.0439	0.0378	1.161	0.24610
41. SwitchY:SpliceI:BLP	-0.0573	0.0129	-4.445	8.85e-06 ***
42. SwitchY:SpliceX:BLP	-0.0405	0.0129	-3.150	0.00164 **
43. Lin:SwitchY:SpliceI:BLP	0.0194	0.0508	0.381	0.70289

44. Lin:SwitchY:SpliceX:BLP	-0.0501	0.0507	-0.988	0.32298
45. Quad:SwitchY:SpliceI:BLP	0.0488	0.0503	0.970	0.33199
46. Quad:SwitchY:SpliceX:BLP	0.0144	0.0502	0.286	0.77465
47. Cub:SwitchY:SpliceI:BLP	-0.1122	0.0500	-2.244	0.02488 *
48. Cub:SwitchY:SpliceX:BLP	-0.0264	0.0500	-0.528	0.59719

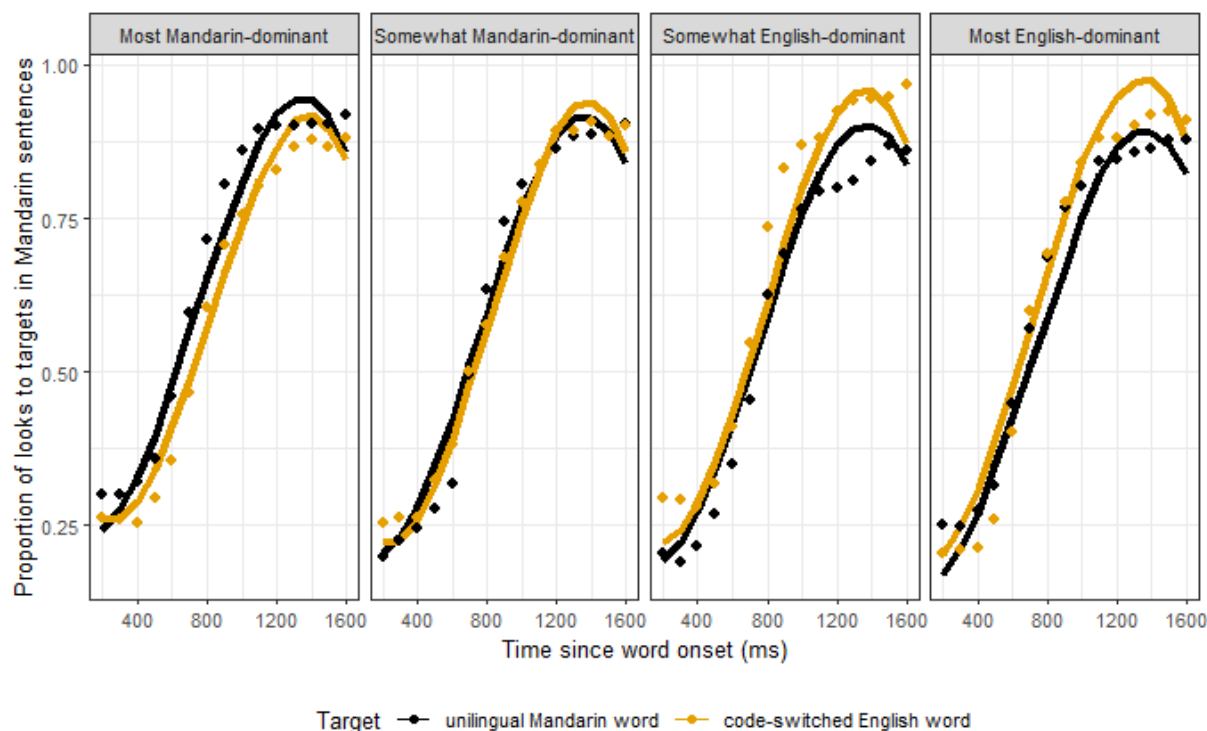
Groups	Name	Variance	Std.Dev.	Corr.		
Subject:Splice	(Intercept)	0.003212	0.05668			
	ot1	0.024932	0.15790	-0.30		
	ot2	0.006914	0.08315	-0.17	-0.66	
	ot3	0.003191	0.05649	0.24	-0.69	-0.03
Subject	(Intercept)	0.003222	0.05676			
	ot1	0.015282	0.12362	0.40		
	ot2	0.019710	0.14039	-0.99	-0.51	
	ot3	0.002356	0.04854	0.32	-0.74	-0.21
Target	(Intercept)	0.009042	0.09509			
	ot1	0.037083	0.19257	0.67		
	ot2	0.015380	0.12402	-0.81	-0.38	
	ot3	0.007751	0.08804	-0.22	-0.83	-0.20
Residual		0.131210	0.36223			

**Table 13.** Fixed and random effects of growth curve analysis of Experiment 3 eye-tracking data: Looks to targets in English sentences, as a function of Switch, Splice, and Dominance.



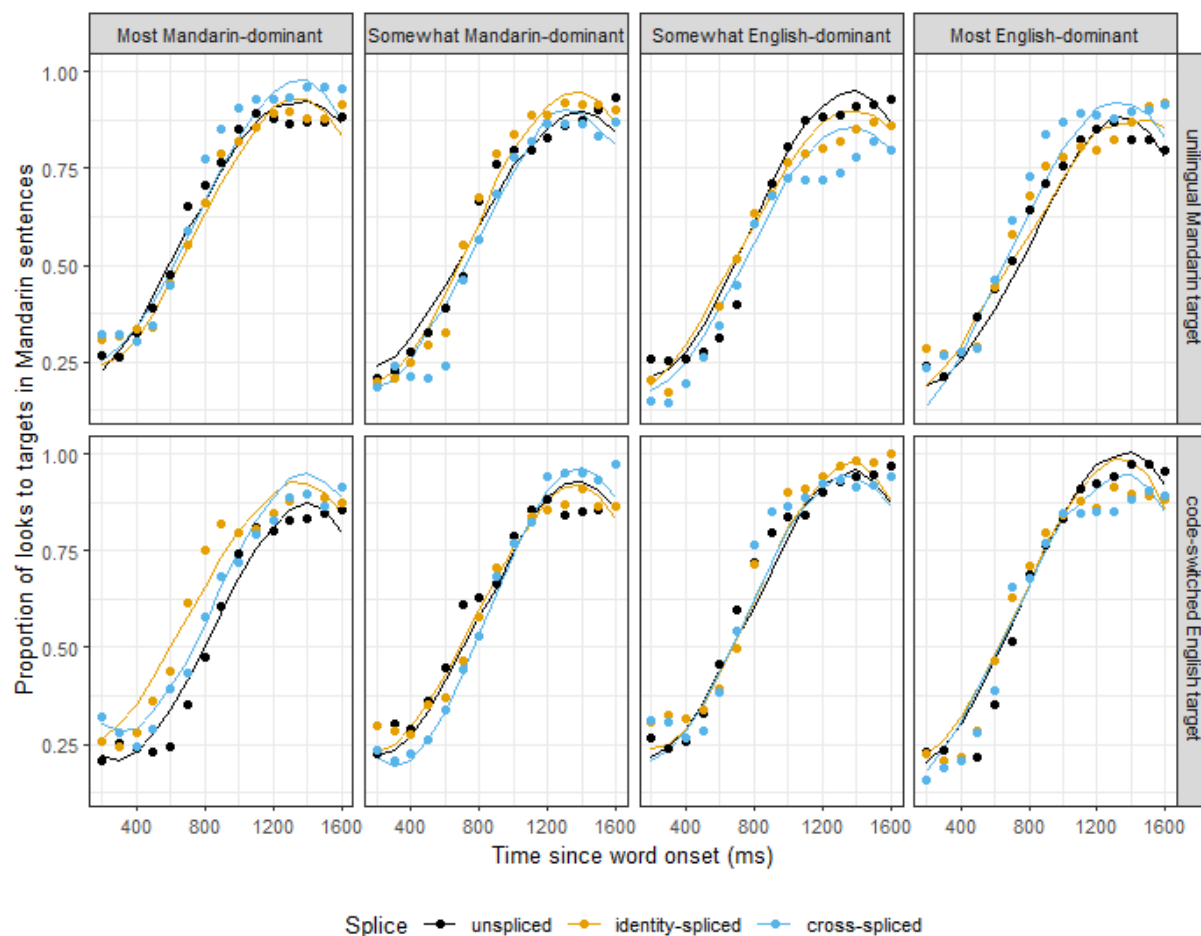
**Figure 26.** Empirical data (points) and model fit (lines) for proportion of looks to targets in Mandarin sentences, by Switch, across all participants and trials.

The interaction between Switch and Dominance was significant, with more looks toward code-switched English targets when the participants scored as more English-dominant ( $Est = .08$ ,  $SE = .009$ ,  $p < .001$ ). This is consistent with the results of Experiment 2, with bilinguals more easily recognizing code-switches in their dominant language, but is different from language production findings. Given the initial result that for balanced bilinguals, there is no switch cost in Mandarin sentences, this result further suggests that whether the listener experiences a switch cost might depend on their degree of dominance in Mandarin and English (Figure 27). The interaction between the quadratic polynomial, Switch, and Dominance was also significant, indicating that the rate of looks toward code-switched English targets increased more slowly when the participant scored as more English-dominant (Table 13; row 33).



**Figure 27.** Empirical data (points) and model fit (lines) for proportion of looks to targets in Mandarin sentences, by Switch and Dominance, across all participants and trials.

While there was no significant interaction between Switch and Splice (Table 13; rows 18-19), the three-way interactions between Switch, Splice, and Dominance was significant: participants who were more English-dominant looked less toward identity-spliced ( $Est = -.05$ ,  $SE = .01$ ,  $p < .001$ ) and cross-spliced English code-switched targets ( $Est = -.04$ ,  $SE = .01$ ,  $p = .002$ ), compared to Mandarin-dominant participants. This suggests that while English-dominant listeners were affected by phonetic cues being withheld, Mandarin-dominant listeners were unaffected (Figure 28). The interaction between the cubic orthogonal polynomial, Switch, Splice (identity-spliced), and Dominance was also significant, suggesting that the rate of looks to identity-spliced code-switched English targets increased slower for bilinguals who were more English-dominant (Table 13; row 47).



**Figure 28.** Empirical data (points) and model fit (lines) for proportion of looks to targets in Mandarin sentences, by Switch, Splice, and Dominance, across all participants and trials.

*Post-hoc analysis: Identity-splicing vs. cross-splicing*

This post-hoc analysis considered whether identity-splicing and cross-splicing resulted in differences in looks to targets in Mandarin sentences. The model remained the same, other than the removal of unspliced tokens. There was no significant difference between looks to identity-spliced and cross-spliced targets, but the interaction between Switch and Dominance was significant ( $Est = .19, SE = .009, p = .03$ ), with more looks to code-switched targets when the participant was more Mandarin-dominant. This latter finding replicates that in the original analysis. Therefore, there was no difference in the effects of the two types of splicing on looks to targets.

*Post-hoc analysis: No splicing vs. any splicing*

This analysis considered identity- and cross-spliced tokens together as spliced tokens and compared them to unspliced tokens, to determine whether there was a general difference between trials with spliced vs. unspliced targets. The model remained the same otherwise. There was no significant difference between looks to unspliced and spliced targets, but Dominance was significant, with fewer looks to unilingual unspliced targets when the listener was more English-

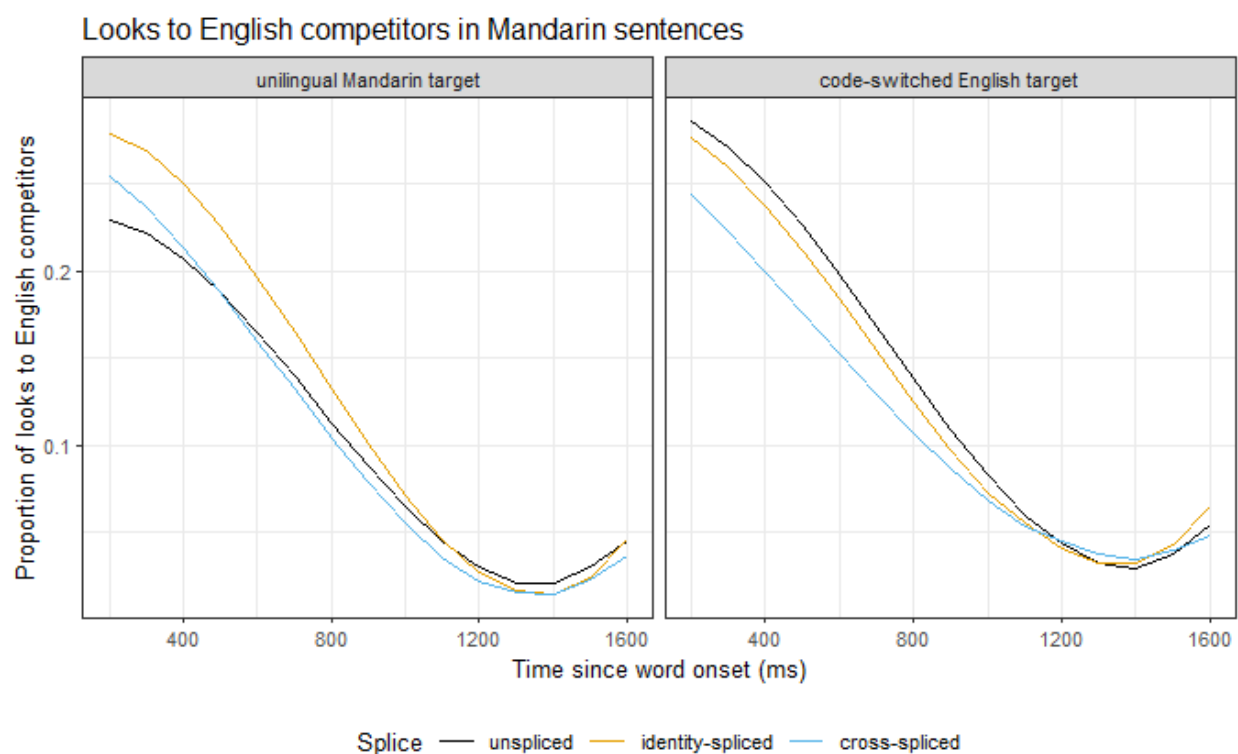


dominant than Mandarin-dominant ( $Est = -.03, SE = .01, p = .05$ ). The interaction between Switch and Dominance was significant ( $Est = .08, SE = .009, p < .001$ ), with more looks to code-switched targets when the participant was more English-dominant than Mandarin-dominant. The three-way interaction between Switch, Splice, and Dominance was also significant ( $Est = -.05, SE = .01, p < .001$ ), with fewer looks to spliced code-switched targets when the participant was more English-dominant than Mandarin-dominant. These effects replicate those of the original analysis. With Mandarin sentence stimuli, therefore, there was no difference between being unspliced, identity-spliced, or cross-spliced, on looks to targets.

### *Looks to English competitors in Mandarin sentences*

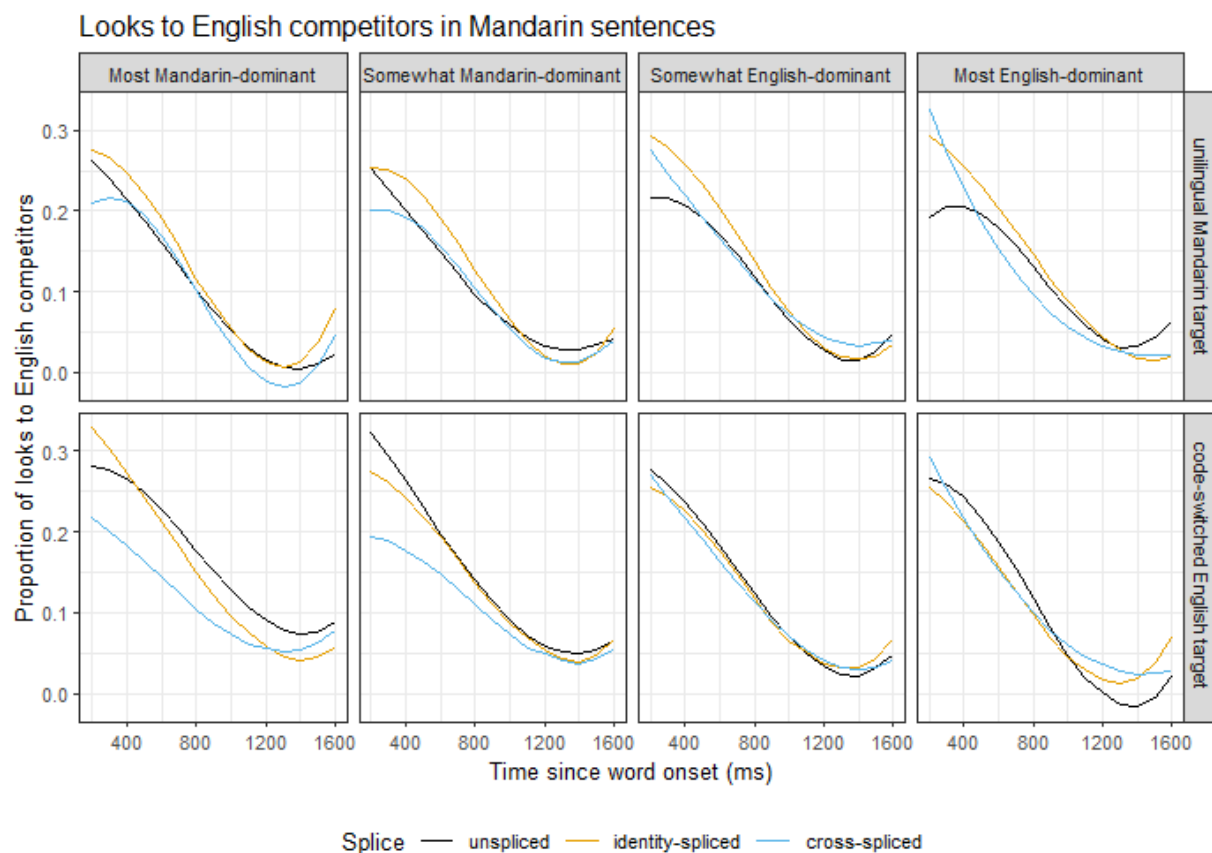
The analysis for looks to English competitors in Mandarin sentences considered a three-way interaction between Switch, Splice, and Dominance, and up to third-order orthogonal polynomials (Appendix H). The random slopes were by-subject, by-target, and subject-by-splicing. Recall that the analysis for looks to English targets in Mandarin sentences found no switch cost, though English-dominant listeners looked more toward English code-switches compared to Mandarin-dominant listeners, but did less well when those code-switches were spliced.

Switch was not significant, so that listeners did not look more or less toward English competitors when the target was an English code-switch (Figure 29;  $Est = .02, SE = .01, p = .1$ ). English code-switched targets in Mandarin sentences did not incur a switch cost anyway, so this result is not unexpected.



**Figure 29.** Model fit (lines) for proportion of looks to English competitors in Mandarin sentences, by Switch and Splice, across all participants and trials.

The interaction between Switch and Dominance was significant: English-dominant bilinguals were less likely to look at the English competitor on trials with English code-switched targets, compared to Mandarin-dominant bilinguals ( $Est = -.03$ ,  $SE = .007$ ,  $p < .001$ ). Compared to the Mandarin target-competitor pairs, which are monosyllabic or bisyllabic, English target-competitor pairs are less similar overall, so this could be an indication of low confusability. Alternatively, the natural phonetic context of the code-switch did not bias listeners toward English in general. The three-way interaction between Switch, Splice (cross-spliced), and Dominance was significant as well: English-dominant bilinguals looked at English competitors more when the target was a cross-spliced English code-switch (Figure 30;  $Est = .02$ ,  $SE = .01$ ,  $p = .02$ ). There were several other significant effects, which can be found in Appendix H.



**Figure 30.** Model fit (lines) for proportion of looks to English competitors in Mandarin sentences, by Switch, Splice, and Dominance, across all participants and trials

### *Interim summary*

Mandarin code-switches in English sentences incurred a switch cost for listeners regardless of dominant language. There was an unexpected effect of the cross-splicing manipulation, which was intended to withhold anticipatory phonetic cues to code-switches, but instead served as an advantage to recognizing Mandarin code-switches, but only for Mandarin-dominant listeners. English-dominant listeners were more likely to look at Mandarin competitors when the target was a cross-spliced code-switch.

English code-switches in Mandarin sentences only incurred a switch cost for Mandarin-dominant listeners, whereas English-dominant listeners recognized them more quickly than even unilingual Mandarin words. This advantage went away when code-switches were spliced; English-dominant bilinguals looked at English competitors more when the target was a cross-spliced English code-switch. On the other hand, Mandarin-dominant listeners were more likely to look at the English competitor when the target was an unspliced English code-switch.

### *Acoustic analysis*

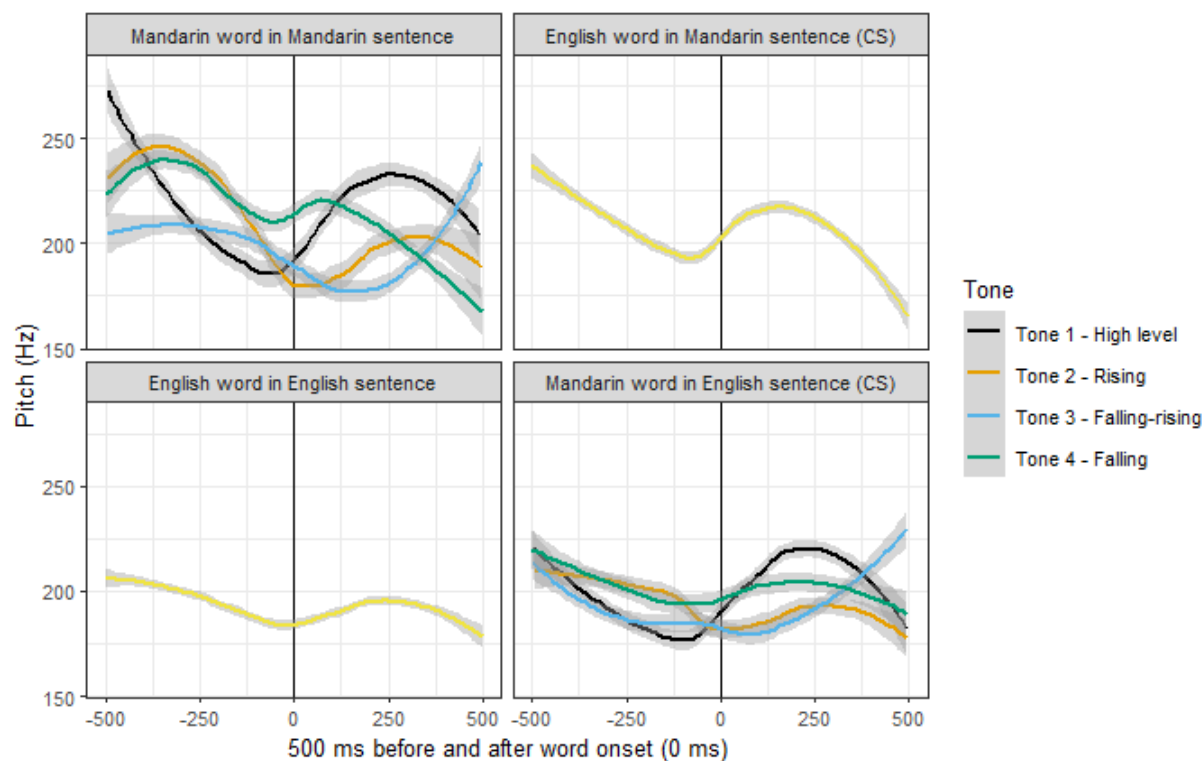
This acoustic analysis focuses on Mandarin and English f0 during code-switching. English words might have wider variation in f0 in code-switched utterances compared to unilingual English utterances, due to the influence of Mandarin lexical tone. Mandarin word tones might be reduced because of the influence of English. The tonal coarticulation patterns that typically lead into Mandarin tones could change, as well as f0 range and extrema.

The acoustic stimuli produced by the bilingual speaker were analyzed using a Praat script that extracted f0 measurements in 10ms intervals from each recorded sentence. Mandarin target words were not balanced with respect to tone: Table 14 shows the number of unilingual and code-switched Mandarin target words that had initial syllables of each tone. Due to the small number of tokens of each tone, this acoustic analysis will qualitatively examine f0 contour plots rather than rely on statistical analysis.

<b>Mandarin target</b>	<b>Tone 1 (high level)</b>	<b>Tone 2 (rising)</b>	<b>Tone 3 (falling-rising)</b>	<b>Tone 4 (falling)</b>	<b>Total tokens</b>
Unilingual	2	4	3	9	18
Code-switched	5	4	3	6	18

**Table 14.** Number of Mandarin targets of each tone.

Figure 31 plots the f0 contours before and after the target word onset. The 500ms following the 0ms vertical line is the f0 contour for the first syllable of the target word. The top row plots f0 before and during target words in Mandarin sentences, while the bottom row plots for English sentences. When the target word is Mandarin, each of the four tones are plotted as its individual f0 contour.



**Figure 31.** Pitch measurements (Hz) 500 ms before and after target onset, by target and sentence language.

The bilingual speaker's  $f_0$  range for Mandarin sentences is clearly broader and higher compared to their  $f_0$  range for English sentences. English target words in Mandarin sentences therefore also have a larger  $f_0$  range, comparable to the range of Mandarin target words in Mandarin sentences. On the other hand, Mandarin target words in English sentences exhibit a smaller  $f_0$  range, comparable to the range of English target words in English sentences. Therefore, code-switched target words showed different  $f_0$  patterns compared to corresponding unilingual target words in the same language. The tones on Mandarin code-switched words were reduced compared to Mandarin unilingual words, while the pitch of English code-switched words was expanded compared to English unilingual words. Specifically, for Mandarin code-switched target words, the tones on the initial syllables differ as follows: tone 1 occurs in a lower  $f_0$  range; tone 2 rises in a more shallow slope and to a lower peak; tone 3 occupies a narrower  $f_0$  range; tone 4 exhibits a lower maximum  $f_0$  and a more shallow slope downwards with a narrower  $f_0$  range.

The 500 ms window preceding the 0ms vertical line shows the  $f_0$  contour leading into the target word. In unilingual Mandarin, anticipatory tonal coarticulation is dissimilatory before tones 1, 2, and 4, but assimilatory before tone 3. These patterns are generally retained but greatly reduced in  $f_0$  range and slope when the Mandarin target word is code-switched.

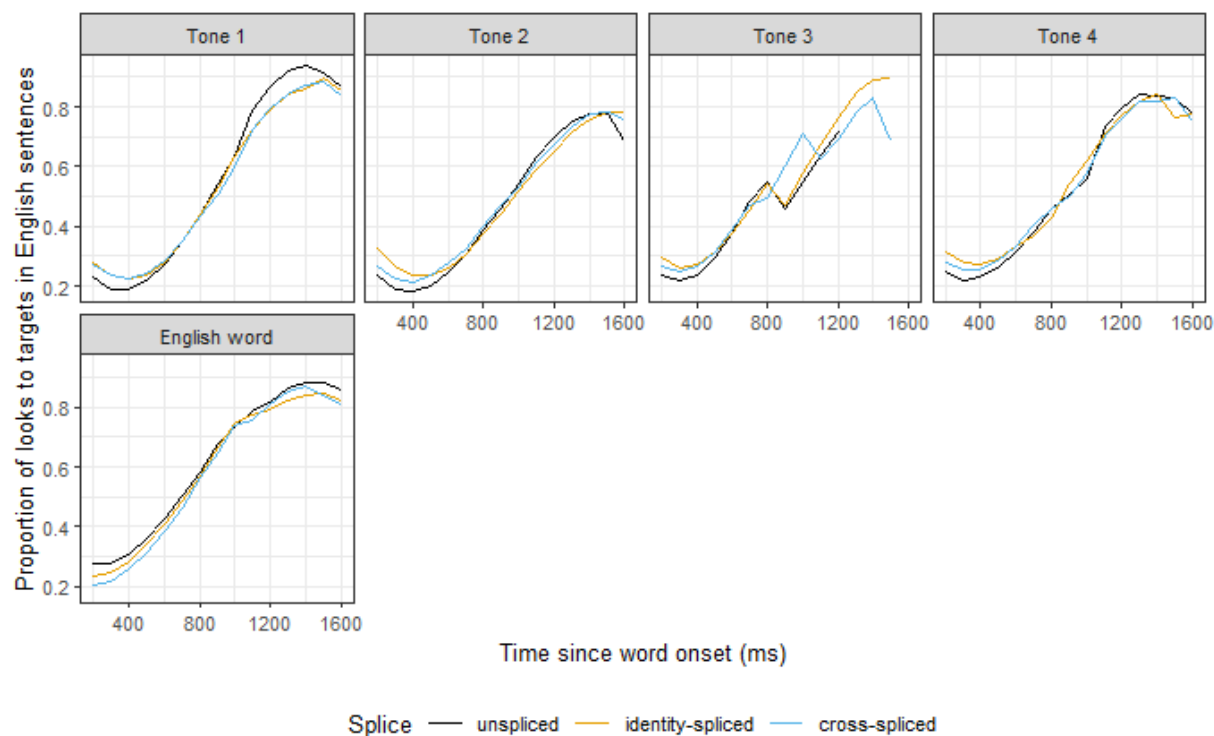
The  $f_0$ s of English target words have a broader range when code-switched vs. when unilingual, and the  $f_0$  preceding the target word is also higher and steeper in code-switched contexts.

It therefore appears that phonetic transfer is bidirectional between Mandarin and English during code-switching, at least for  $f_0$ . The need for  $f_0$  to vary in systematic ways to produce lexical tone in Mandarin affects English pitch: (a) the English context before a Mandarin code-switch takes on the anticipatory tonal coarticulation patterns typical of each Mandarin tone, and (b) an English code-switch in a Mandarin sentence has more variation in pitch than in an English sentence. The lack of lexical tone in English also affects Mandarin: (a) Mandarin code-switches in English sentences have reduced tones compared to their unilingual counterparts, and (b) the Mandarin context preceding an English code-switch has a distinct  $f_0$  contour from any of the coarticulatory  $f_0$  contours in unilingual Mandarin.

Analysis of these sentences showed that  $f_0$  differed in many aspects when comparing unilingual to code-switched utterances. In particular,  $f_0$  is “diminished” before a Mandarin code-switch, with reduced anticipatory tonal coarticulation, while it is “amplified” before an English code-switch. If cuing depends on the “distance”, or overall difference in Hz, between code-switching pronunciation and unilingual speech, then the reduction of tonal coarticulation might hurt recognition of Mandarin code-switches. On the other hand, the availability of coarticulation might aid recognition of each particular code-switch. Besides, though the English context before a Mandarin word occurs in a similar  $f_0$  range as unilingual English context, the exact contours differ, which could actually aid in recognition. For English code-switches, the steep fall in Mandarin  $f_0$  could be useful, particularly since that contour differs from the ones usually preceding Mandarin tones. The shape and steepness of the fall most resembles the contour before tone 1 Mandarin words, but is still less steep, starts lower, and reaches a higher minimum. This means that the context preceding English code-switches is different enough from what precedes Mandarin words with initial syllables of tones 2-4 to be distinguishable, but could possibly be confused with tone 1 anticipatory coarticulation.

Additionally, recognition of a Mandarin word requires recognizing the particular tone of the word in order to distinguish it from lexical competitors with different tones. On the other hand, English words do not have competitors that differ in  $f_0$ , so even a slightly strange preceding  $f_0$  would likely not result in activation of lexical competitors. Recognition of Mandarin and English code-switches might thus differ not just because of the kinds of phonetic transfer they are subject to, but also because of the phonological features of the languages, in this case, how  $f_0$  is utilized phonologically.

Figure 32 plots the eye-tracking results for looks to targets in English sentences by tone, to try to understand why spliced code-switches in English sentences were easier to recognize. Mandarin code-switched targets are plotted by tone in the top row, while English targets are plotted together in the bottom row. Since Mandarin targets were not balanced for tone, there were fewer tone 3 Mandarin targets, resulting in the more jagged curve. There is no obvious tone-related pattern for why spliced code-switches were easier to recognize.



**Figure 32.** Model fit (lines) for proportion of looks to targets in English sentences, by tone, cross, across all participants and trials.

## Discussion

This experiment demonstrated that code-switched Mandarin words in English sentences incur a switch cost, but code-switched English words in Mandarin sentences are not only cost-free but easier to recognize for English-dominant listeners. These results suggest an asymmetry in how Mandarin and English code-switched words are processed in auditory comprehension. This asymmetry is associated with frequency of switch direction and dominant language, but not with phonetic cuing.

Since Mandarin-English bilinguals in the U.S. more frequently insert English words into Mandarin sentences than vice versa, this result also demonstrates an effect of frequency in auditory comprehension. The infrequent type of code-switch incurred a switch cost for all bilinguals, while the frequent type only incurred a cost for bilinguals not dominant in the switch language. Therefore, as hypothesized, frequency aids auditory comprehension of code-switches. This effect of frequency suggests that language exposure and usage can play an important role in bilingual language processing, especially since the majority of participants reported more frequently inserting English words into Mandarin sentences and several commented that Mandarin insertions into English “sounded odd.”

The effects of dominant language were associated with asymmetric switch cost, but only as entwined with sentence language and therefore the frequency effect, rather than with previous literature (i.e., Inhibitory Control Model predictions or language production studies showing that dominant language code-switches incur a greater processing cost). In English sentences, the listener’s dominant language did not affect switch cost at all. Both Mandarin- and English-

dominant bilinguals experienced a switch cost with processing Mandarin code-switches in English sentences, which were the infrequent type of insertion. In Mandarin sentences, dominant language affected switch cost, with a switch cost for processing English code-switches when English was the non-dominant language, but an advantage when English was the dominant language. Mandarin-dominant bilinguals experienced a switch cost while recognizing English code-switches, while English-dominant bilinguals actually had an advantage in recognizing English code-switches, recognizing English code-switches more easily than unilingual Mandarin words in Mandarin sentences.

The experimental splicing manipulation that was meant to test anticipatory phonetic cuing for code-switches produced results that, assuming that it had the intended effect, were not interpretable in any straightforward way. The hypothesis was that if phonetic cuing of code-switches occurs, and listeners are sensitive to it and thus able to anticipate code-switches, then there should be more looks to the target image when the target word is an unspliced code-switch (retains natural phonetic cues) than when it is a cross-spliced code-switch (manipulated to withhold phonetic cues).

In English sentences, cross-spliced unilingual targets were more difficult to recognize compared to unspliced unilingual targets, which was expected because cross-splicing involves splicing unilingual targets into code-switched contexts, so that listeners might expect a code-switch but then not hear one. However, listeners more easily recognized cross-spliced code-switched targets compared to unspliced code-switched targets, which is the opposite of the hypothesis. According to the post-hoc analyses, both kinds of spliced code-switched targets were easier to recognize than unspliced code-switched targets. This result suggests that the splicing process may have resulted in a perceptible oddity that served to cue the upcoming Mandarin code-switch. These Mandarin code-switches in English sentences were also the infrequent type of insertion that rarely occurs in daily bilingual speech; it is possible that the bilingual participants recalibrated to expect more of these infrequent code-switches throughout the course of the experiment, and therefore were better able to manage them with or without the preceding phonetic context. In addition, English-dominant bilinguals were less effective than Mandarin-dominant bilinguals at recognizing spliced Mandarin code-switches in English sentences, which again points to the dominant language code-switch being easier to recognize. Perhaps Mandarin-dominant bilinguals were better able to manage the incongruent context of spliced Mandarin code-switches, due to having more experience with recognizing Mandarin words, possibly being more sensitive to contrastive tone.

In Mandarin sentences, there was no significant difference between participants' ability to recognize unspliced, cross-spliced, and identity-spliced code-switched targets, unless participants' dominant language was accounted for. Firstly, English-dominant bilinguals recognized English code-switches in Mandarin sentences more easily than Mandarin-dominant bilinguals. This is again the dominant language effect that was relatively consistently found throughout this study. But these English-dominant bilinguals were slower than Mandarin-dominant bilinguals in recognizing code-switched English targets when they were identity- or cross-spliced.

For both English and Mandarin sentences, English-dominant bilinguals were slower than Mandarin-dominant bilinguals to recognize spliced code-switches. If the splicing manipulation resulted in perceptibly different stimuli than unspliced stimuli, then perhaps Mandarin-dominant bilinguals have more sensitivity or an advantage in exploiting various acoustic cues. According to participants' self-reports on the code-switching questionnaire, Mandarin-dominant bilinguals

code-switch more often than English-dominant bilinguals, suggesting that more experience with code-switching is beneficial to processing.

Moreover, the analyses of looks to competitors that were in the same language as the code-switched target, e.g. Mandarin competitor in English sentence or English competitor in Mandarin sentence, revealed interesting effects of splicing on participants' looks to competitors. Specifically, with both English and Mandarin sentences, when the target was a cross-spliced code-switch, English-dominant listeners were more likely to look toward same-language competitors. This suggests that cross-splicing influenced English-dominant listeners toward Mandarin competitors rather than Mandarin code-switched targets and English competitors rather than English code-switched targets. English-dominant listeners were therefore less effective than Mandarin-dominant listeners at identifying cross-spliced code-switches because they were looking toward competitors in the switch language instead. Perhaps there was some perceptible acoustic difference that they were sensitive to, but their lack of experience with code-switching resulted in more consideration of the competitor as the potential target.

It was unclear from the results of this experiment whether the splicing manipulation reflected the absence of anticipatory phonetic cues to code-switches. Splicing effects were dependent on dominant language in both English and Mandarin sentences. The bilingual speaker for this experiment did produce somewhat reduced tones in Mandarin code-switches compared to the speaker for the experiments in the previous chapter. We therefore turn to the acoustic analysis to interpret these results.

A different speaker than the one who produced the stimuli for Experiments 1-2 recorded for the current experiment. The acoustic analysis of this speaker's recordings makes it clear that phonetic patterns occurred that *could* have functioned as anticipatory phonetic cuing. Code-switching between Mandarin and English resulted in some bidirectional phonetic transfer, where the f0 of both code-switches and code-switching contexts is different from typical f0 ranges, slopes, and values in comparable unilingual utterances. Specifically, her productions of code-switched Mandarin words are less tonal compared to unilingual Mandarin words and the anticipatory pitch coarticulation that normally precedes unswitched Mandarin words is diminished before code-switched Mandarin words. Similarly, her English words display a more dynamic pitch contour and range. If this speaker's Mandarin sounds more English-like *and* her English sounds more Mandarin-like, then the speaker is engaging in blending of the phonetics of both languages and anticipatory phonetic cuing might not occur, depending on the degree of phonetic blending. These results do not lead to the generalization that anticipatory phonetic cuing does not occur before code-switching in all Mandarin-English bilingual speakers. There is individual variation among Mandarin-English bilinguals, including in the way that they produce code-switched speech. Possibly, some speakers blend aspects of both languages, while others do not, or do so to a lesser degree.

The acoustic analysis suggests that some of the Mandarin competitors in this experiment might have influenced the results. A Mandarin target word that is less tonal in a code-switched context is more likely to be confused with a Mandarin competitor, especially for Mandarin target-competitor pairs that are segmental homophones but differ in tone. If the speakers' tones are reduced, then the Mandarin target and Mandarin competitor will sound more similar, especially if they are otherwise homophones. In fact, plotting looks to these several of these pairs indicates that on some trials, certain listeners were unable to identify certain target words, never fixating on the correct target, but rather on a competitor. For instance, this happened with Mandarin targets and their within-language competitors: e.g., *xīng* [ɕiŋ<sup>55</sup>] 'star' and *xīn* [ɕin<sup>55</sup>]



'heart', which only in the place of articulation of the word-final nasal (respectively velar and alveolar). This also occurred with Mandarin targets and cross-language competitors, e.g. *shù* [ʃu<sup>51</sup>] 'tree' and *shoe* [ʃu], which differ in presence/absence of tone and the place of articulation of the word-initial fricatives (respectively retroflex and post-alveolar). Qualitative evaluation by listening to these stimuli suggests that accented pronunciations of certain segments and reduced tones are responsible for perceptual confusion. Appendix I shows raw data plots for targets that were not recognized, along with looks to their competitors.

## Conclusion

The results of this experiment contribute to work on switch costs, demonstrating with eye-tracking evidence from Mandarin-English bilinguals that code-switches do not always incur processing costs in auditory comprehension. While Chapter 2 solely investigated the cost of recognizing Mandarin words in English sentences, this chapter compared costs between Mandarin and English code-switched words, and found a switch cost asymmetry by sentence language, likely modulated by the frequency of the type of code-switch, and therefore bilingual experience. This experiment replicated the switch cost found for Mandarin code-switched words, and additionally found that the listener's dominant language influences not only the presence or absence of switch costs for English code-switched words, but the degree of that cost. While the phonetic context of code-switches did not appear to aid in recognition, contrary to Experiment 2 findings, there is evidence that the production patterns of a particular bilingual speaker can affect the presence of phonetic cues and therefore the ease with which the listener recognizes code-switches. This is evidence from bilingual code-switching of the link between speech production and auditory comprehension.

## Chapter 4. Conclusion

This dissertation consists of three experiments, discussed in Chapters 2 and 3, which were designed to test whether (a) Mandarin and English code-switches incur a processing cost in auditory comprehension, (b) bilingual listeners recruit anticipatory phonetic cues during recognition of code-switches, and (c) whether switch costs were asymmetric due to frequency and dominant language. I found that:

- Recognition of Mandarin words in English sentences, which are infrequent in code-switching, comes with a switch cost.
- Recognition of English words in Mandarin sentences, which are frequent in code-switching, only comes with a switch cost if the listener is not English-dominant.
- Bilingual listeners may recruit anticipatory phonetic cues during the recognition of code-switches, depending on the speaker's production patterns

Experiment 1 (Chapter 2) employed a concept monitoring experiment to test whether there was a switch cost for recognizing Mandarin words in English sentences. Bilingual Mandarin-English listeners were slower to recognize code-switches compared to unilingual words, indicating a switch cost. The presence of anticipatory phonetic cues did not aid in listeners recognizing code-switches more quickly, compared to when cues were withheld.

Experiment 2 (Chapter 2) used an eye-tracking experiment to test whether listeners were sensitive to anticipatory phonetic cues. The results, which show real-time processing, indicated that code-switches were indeed more difficult to recognize than unilingual words, and the presence of anticipatory phonetic cues aided in the recognition of sentence-medial code-switches. Taken together with the results of Experiment 1, it would seem that the effect of anticipatory phonetic cues is too small to be obvious through an offline processing measure.

Experiment 3 (Chapter 3) employed another eye-tracking experiment to compare whether recognition might differ for English words in Mandarin sentences vs. Mandarin words in English sentences. Results indicated an asymmetric switch cost that was dependent on the language of the code-switch and the sentence. Mandarin words in English sentences, as in Experiments 1 and 2, incurred a switch cost in recognition. English words in Mandarin sentences incurred a switch cost with Mandarin-dominant bilinguals, but were easier to recognize than even unilingual Mandarin words for English-dominant bilinguals. Participants had reported infrequently inserting Mandarin words in English sentences compared to English words in Mandarin sentences, suggesting that experience can affect processing cost. However, this experiment did not find any effects of anticipatory phonetic cues for either kind of code-switch.

While Experiments 1 and 2 utilized recordings from one bilingual speaker, Experiment 3 stimuli were recorded by a second bilingual speaker. Acoustic analysis showed that both speakers produced tone-specific patterns of anticipatory coarticulation in f<sub>0</sub>, so that Mandarin code-switched words in bilingual speech are subject to the same kinds of patterns as shown in unilingual Mandarin speech (Xu, 1997). There were differences between the two speakers in their degree of coarticulation. The first speaker appeared to produce very strong pitch contours in anticipatory tonal coarticulation before Mandarin code-switches, although there were no recordings of unilingual Mandarin sentences to conduct a full comparison of her tonal coarticulation. The second speaker produced both English and Mandarin unilingual and code-

switched sentences, so it was possible to fully compare her pitch in these different contexts. Her code-switched utterances with Mandarin targets, relative to corresponding unilingual utterances, were characterized by reduced Mandarin tones on the target words, and preceding anticipatory tonal coarticulation. Her code-switched utterances with English targets, compared to corresponding unilingual English utterances, showed amplified English pitch. In fact, the bilingual participants could not tell apart targets and competitors on several trials (see Appendix I), possibly due to reduced tones and accentedness resulting from bidirectional phonetic transfer. These results taken together suggest that the production patterns of the bilingual speaker have a direct influence on the functionality of anticipatory phonetic cues in the auditory comprehension of code-switches.

These conclusions should be taken in the context of Mandarin-English code-switching and the specific speakers. Previous studies have shown effects of anticipatory phonetic cues on the recognition of Spanish-English code-switching, particularly for VOT and intonation (Fricke et al., 2016; Piccinini & Garellek, 2014). Phonetic features may function differently when it comes to cuing. With VOT, there have been relatively consistent results showing that during code-switching, bilingual speakers of long-lag and short-lag VOT languages produce the same phonetic patterns: long-lag VOTs shorten. With intonation, the only evidence for phonetic cuing comes from Piccinini and Garellek's (2014) study that analyzes the productions of one speaker; comparing other speakers may reveal variation. In Mandarin-English code-switching, there may be other phonetic features contributing to anticipatory cuing, but I have focused on tone and pitch thus far. Mandarin has four lexical tone categories, and with anticipatory tonal coarticulation preceding each tone, there are many ways for a speaker's productions to fluctuate. This may contribute to somewhat different results in recognition studies on Mandarin code-switching, compared to other phonetic features.

Moreover, the speaker's "accentedness" during code-switching could affect recognition. Even if a bilingual speaker does not "sound accented" during unilingual speech, the simultaneous use and therefore activation of both languages can result in what is called the phonetic reflexes of code-switching, which can be thought of as accentedness during bilingual language mode. This accentedness may or may not aid in recognition. If a phonetic pattern that is very unique to code-switching is being produced, then code-switches would be cued. If the result of phonetic transfer is that lexical tone, which distinguishes between several words sharing all the same segments, is reduced, then the problem in auditory comprehension is not solely code-switching but also selecting the correct lexical item and not its phonological competitors without fully informative acoustic information.

In addition to variation between speakers, inter-listener variation can also contribute to differences in recognition. Studies have shown that bilinguals who are frequent code-switchers are better at handling non-linguistic task-switching, due to an advantage in cognitive control, which is necessary in language as well to regulate when one language is being used versus the other (Prior & Gollan, 2011; Verreyt, Woumans, Vandelandotte, Szmalec, & Duyck, 2015). For example, bilingual listeners with more experience code-switching might adapt more quickly to language switches, due to having the practice. They could additionally be more adept at detecting the subtle acoustic cues preceding a code-switch. Experiments 2 and 3 have shown that the listener's dominant language, which encompasses experience through history and usage, can affect processing. It is also possible that more experience code-switching with a particular individual attunes the bilingual's comprehension system to the specific frequency and patterns of code-switching. This could consist of exemplar-based perception, or general patterns such as if

an interlocutor frequently code-switches over to English when talking about school-related topics.

Evidence for the role of experience in processing is clear from Experiment 3, which shows that more frequently encountered code-switches do not necessarily incur a switch cost. While the bilinguals in the current study reside in a predominantly English-speaking environment, future research can examine Mandarin-English bilinguals in a primarily Mandarin-speaking environment, or even a multilingual environment like Singapore where code-switching occurs more frequently in general. In these cases, Mandarin words in English sentences may occur more often in code-switching, which would allow for further testing of the frequency hypothesis.

The findings relating to dominant language suggest that more work needs to be done in the realm of auditory comprehension. A previous finding on auditory comprehension found effects of dominant language that were consistent with the predictions of the Inhibitory Control Model, with Spanish-English listeners being slower to recognize code-switches in their dominant language (Olson, 2017). The findings of Experiments 2 and 3 showed instead that Mandarin-English listeners could be faster to recognize code-switches in their dominant language, instead, so that a bilingual's experience and use of a language can contribute to processing. Thus, it is as yet uncertain whether any of these findings can be generalized to the auditory comprehension of code-switching, especially since different bilingual communities code-switch differently. The difference not only in language pairs but in the daily experience of code-switching can very reasonably affect processing.

Indeed, the study of Mandarin and English in particular as a language pair has revealed that more work is needed in this domain, not only to reconcile differences from studies on Spanish and English (such as Olson, 2017) but also to investigate other language pairs and how phonetic features can differ in cue-functionality to affect recognition. While these experiments sought to approximate natural code-switching, which primarily occurs in spoken conversation, future studies can improve upon the stimuli, by using sentences with larger code-switched chunks, which occur more frequently than single word insertions.

In conclusion, code-switching is a multidimensional bilingual phenomenon that we have only just begun to understand. Code-switches can vary in length in an utterance (i.e., single word vs. larger constituents). Speakers may have different motivations for code-switching, whether on the community-level – e.g. residing in a multilingual environment where bilingual language mode is the norm – or on the individual-level – feeling that a certain concept is better expressed in one language than the other – or at the conversational level – often code-switching with a particular interlocutor. Individual speakers of a particular language pair can vary in their productions of phonetic features during code-switching, resulting in unique patterns that may or may not function as anticipatory cues for listeners during recognition. Additionally, code-switching in a natural spontaneous setting might differ from a laboratory setting, hinging on the language mode of the experiment and even the bilingualism of the experimenters. All of these are just a few of the factors that can affect whether code-switches incur a processing cost, and furthermore these effects can differ depending on whether the process is production or comprehension.

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## Appendices

### Appendix A

*Experiment 1 auditory stimuli. Target words are underlined. Chinese target words are in Pinyin, with English translations enclosed in parentheses. For catch trials, the word heard in the sentence is underlined and the word corresponding to the pictured object is in brackets.*

Target trials:

1. We got a qì qiú (balloon) for her birthday.
2. She saw a wáng guān (crown) in the museum.
3. They could see the líng dāng (bell) from the window.
4. He found his pí dài (belt) in the drawer.
5. I took the yùn dǒu (iron) from the shelf.
6. She picked up the xiàng liàn (necklace) from the dresser.
7. He put his xuē zi (boots) by the door.
8. I used the sào zhou (broom) to sweep the floor.
9. They looked for a shuā zi (brush) in the room.
10. We saw the māo tóu yīng (owl) in the tree.
11. We heard the dà pào (cannon) from far away.
12. He picked up the máo mao chóng (caterpillar) from the leaf.
13. We needed a nán guā (pumpkin) for the pie.
14. She observed the wō niú (snail) on the wall.
15. I found a cāng ying (fly) in my house.
16. He searched for his kù zi (pants) in the pile.
17. They watched the movie about the xiaǒ chǒu (clown).
18. I moved the papers on his zhuō zi (desk).
19. He took the letter out of the xìn fēng (envelope).
20. I wanted the dessert with the caǒ méi (strawberry).
21. She practiced the piece on her dízi (flute).
22. He saw a child with a sōng shǔ (squirrel).
23. They watched the game of gǎn lǎn qiú (football).
24. We read the story about the qīng wā (frog).
25. She wanted the guide to talk about the cháng jǐng lù (giraffe).
26. We picked up the cage of the zhà měng (grasshopper).
27. I reached for the dress on the yī jià (hanger).
28. He heard the music of the shù qín (harp).
29. They found the wreck of the zhí shēng jī (helicopter).
30. She broke the string on her xiǎo tí qín (violin).
31. We watched the documentary on the qǐě (penguin).
32. I handed the waiter the jiǔ bēi (wine glass).
33. I passed her house on the way home.
34. He used the kettle on the counter.
35. We stared at the moon in the sky.
36. She bought a bike from her neighbor.
37. They looked for the needle in the haystack.



38. We listened to the bird in the tree.
39. I used the pepper in my stirfry.
40. She put the orange in the bowl.
41. They wanted the cake from the bakery.
42. He found a peanut in his pocket.
43. She took the pencil from the case.
44. I played the piano in the hall.
45. She found her purse in the closet.
46. I needed a chain for my bike.
47. We saw the church on the hill.
48. They heard the clock in the hall.
49. She took the box with the ring.
50. I wore the sweater with the skirt.
51. They found the web of a spider.
52. We saw the plane above a cloud.
53. He saw the wings of a swan.
54. They looked for the clues by the fence.
55. He broke the bones in his finger.
56. We wanted the sauce on the fish.
57. She heard the cry of the rooster.
58. I broke the nail of my toe.
59. They chased the thief onto the train.
60. I moved the furniture with the truck.
61. He saw the outline of the foot.
62. They found the body in the well.
63. I took the cans that were near the wheel.
64. We watched the scene from the window.

Catch trials:

65. She chose the gown for the party. [lemon]
66. He took the bù dāi (pouch) from the man. [banana]
67. They led the girl away from the van. [barn]
68. We got a dìng shū jī (stapler) for class. [nail]
69. I saw a raccoon behind the plant. [zebra]
70. They asked for the sofa on the right. [barrel]
71. I wanted the guàn tóu (tin) for my collection. [anchor]
72. He brought the package in from the porch. [accordion]
73. She gave a rock to the xiǎo hái (child). [sweater]
74. They bought a sofa but not a coffee table. [bed]
75. I noticed the wagon by the nóng mǐn (farmer). [donkey]
76. We asked for a drink after having the meal. [cigarette]
77. He saw a gē zi (pigeon) next to the shed. [skunk]
78. They found a bug on the pán zi (plate). [asparagus]
79. She considered the size of the huǒ jiàn (rocket). [cow]
80. We spotted the location of the treasure. [lobster]

## Appendix B

Experiment 2 visual stimuli. Mandarin words corresponding to images are in Pinyin, with English translations enclosed in parentheses.

Target	Cross-language Competitor	Within-language Competitor	Distractor
<i>English target</i>	<i>Mandarin cohort</i>	<i>English cohort</i>	<i>Distractor</i>
bee	bǐ (pen)	beans	candle
beetle	bí zi (nose)	beer	camel
mountain	māo (cat)	mouth	bear
lamp	lán zi (basket)	ladder	airplane
goat	gǒu (dog)	gorilla	kangaroo
monkey	mén (door)	mushroom	fox
artichoke	ěr duo (ear)	arm	peach
diamond	dài zǐ (ribbon)	dice	glasses
leaf	lí zi (pear)	leek	key
shark	xiàng (elephant)	shovel	refrigerator
tulip	tǔ dòu (potato)	tuba	ruler
bus	běn zi (notebook)	butterfly	turtle
coat	kòu zi (button)	comb	vase
pipe	pái (playing cards)	pineapple	hammer
cherry	qíe zi (eggplant)	chair	suitcase
bomb	bāo (bag)	box	lock
phone	fēng chē (windmill)	fork	stove
tiger	taì yáng (sun)	tie	horse
<i>Mandarin target</i>	<i>English cohort</i>	<i>Mandarin cohort</i>	<i>Distractor</i>
píng zi (bottle)	pig	píng guǒ (apple)	alligator
xī hóng shì (tomato)	sheep	xī guā (watermelon)	eagle
mào zi (hat)	mouse	mào jīn (towel)	flower
lán qiú (basketball)	lantern	la' n bǎo shí (sapphire)	pot
sháo zi (spoon)	saw	shào zi (whistle)	toaster
bēi zi (cup)	baby carriage	bèi zi (quilt)	umbrella
bào zi (leopard)	ball	bào zhǐ (newspaper)	rabbit
miàn bāo (bread)	meat	miàn tiáo (noodles)	carrot
qì chē (car)	cheese	qí zi (flag)	onion
dì tú (map)	deer	diàn shì (television)	lion
xīn (heart)	ship	xīng (star)	scissors
lǐ zi (plum)	leash	lǐ wù (gift)	corn
shū (book)	shoe	shù (tree)	knife
tāng (soup)	taco	táng (candy)	grapes
wá wa (doll)	watch	wà zi (sock)	toothbrush
shǒu tào (glove)	soda	shǒu jī (cellphone)	kite
kǒng què (peacock)	coal	kǒng lóng (dinosaur)	drum
dēng pào (lightbulb)	duck	dèng zi (stool)	ant

### Appendix C

*Experiment 2 auditory stimuli. Target words are underlined. Chinese target words are in Pinyin, with English translations enclosed in parentheses.*

1. I saw the bee near the table.
2. He noticed the tulip on the floor.
3. They talked about the mountain while in the car.
4. She was curious about the lamp on the table.
5. We remarked on the monkey outside the house.
6. I was confused about the artichoke on the counter.
7. They bought the diamond from the store.
8. He took the leaf from the tree.
9. We watched the goat from a distance.
10. They were interested in the story about the shark.
11. I heard the boy talk about the beetle.
12. We used the camera to photograph the bus.
13. She was upset that the woman didn't have the coat.
14. I questioned whether the man had the pipe.
15. He glanced at the picture of the cherry.
16. They saw the man put down the bomb.
17. We needed the man to find us a phone.
18. She saw a picture of the tiger.
19. I saw the píng zi (bottle) in the backyard.
20. We found the xī hóng shì (tomato) in the truck.
21. We saw the mào zi (hat) in the tree.
22. He brought the lán qiú (basketball) to the team.
23. I moved the shaó zi (spoon) to the side.
24. She bought the bēi zi (cup) for her sister.
25. They noticed the bào zi (leopard) in the enclosure.
26. We prepared the miàn bāo (bread) for dinner.
27. I took the qì chē (car) to the garage.
28. I knew that the story was not about a dì tú (map).
29. They looked for the lady with a xīn (heart).
30. He explained that the container was not for the lí zi (plum).
31. He placed the wallet near the shū (book).
32. They wanted the meal without the tāng (soup).
33. I bought the other item as well as the wá wa (doll).
34. She needed the neighbor to show her the shǒu tàò (glove).
35. We knew that the movie did not feature any kǒng què (peacock).
36. He found the room that had the dēng pào (lightbulb).

## Appendix D

*The following is a copy of my code-switching questionnaire, which adapted sections of a language history questionnaire used by the labs of Drs. Paola Dussias and Judith Kroll, and shared with me by Dr. Rhonda Mudry.*

### Code Switching Questionnaire

#### A. Identity and background

1. Growing up, did your parents or primary caretakers speak more than one language to you?
2. What language(s) do your parents or primary caretakers use to speak to you?
3. Please rate your level of proficiency in speaking, reading, writing, and understanding in each language, using a scale of 0 (not well at all) – 6 (fluently).

	Speaking	Reading	Writing	Understanding
<b>Mandarin</b>				
<b>English</b>				
<b>Other (list any):</b>				

4. How would you feel if you were referred to as Chinese and/or a Mandarin speaker?
5. How would you feel if you were referred to as American and/or an English speaker?

#### B. Interactional context

1. How many waking hours on an average day do you typically spend in each of these contexts? If the answer for any option is “none”, please write 0.

Home (current residence):

School:

Work:

Free time:

2. On a scale of **1-9**, with 1=Never and 9=Always, evaluate the degree to which the following statements reflect your language experience with speaking English and Mandarin at home (i.e. with family):

- a. When I talk to family members at home, I use more than one language.

1      2      3      4      5      6      7      8      9

- b. I sometimes begin a sentence in one language and finish it in another language.

1      2      3      4      5      6      7      8      9

3. On a scale of 1-9, with 1=Never and 9=Always, evaluate the degree to which the following statements reflect your language experience with speaking English and Mandarin at home (i.e. your residence in the Bay Area):

a. When I talk to roommates/housemates, I use more than one language.

1      2      3      4      5      6      7      8      9

b. I sometimes begin a sentence in one language and finish it in another language.

1      2      3      4      5      6      7      8      9

4. On a scale of 1-9, with 1=Never and 9=Always, evaluate the degree to which the following statements reflect your language experience with speaking English and Mandarin at school:

a. When I talk to people at school, I use more than one language.

1      2      3      4      5      6      7      8      9

b. I sometimes begin a sentence in one language and finish it in another language.

1      2      3      4      5      6      7      8      9

5. On a scale of 1-9, with 1=Never and 9=Always, evaluate the degree to which the following statements reflect your language experience with speaking English and Mandarin at work: (If you don't work, leave this question blank.)

a. When I talk to people at work, I use more than one language.

1      2      3      4      5      6      7      8      9

b. I sometimes begin a sentence in one language and finish it in another language.

1      2      3      4      5      6      7      8      9

6. On a scale of 1-9, with 1=Never and 9=Always, evaluate the degree to which the following statements reflect your language experience with speaking English and Mandarin during free time:

a. When I talk to people in my free time, I use more than one language.

1      2      3      4      5      6      7      8      9

b. I sometimes begin a sentence in one language and finish it in another language.

1      2      3      4      5      6      7      8      9

### C. Switching/mixing languages

On a scale of **1-5**, with 1=Never and 5=Always, evaluate the degree to which the following statements are representative of the way you speak in the languages you know.

1. I tend to switch languages during a conversation (e.g. I switch from Mandarin to English and vice versa).

1      2      3      4      5

2. When I cannot recall a word in English, I tend to immediately produce it in Mandarin.

1      2      3      4      5

3. When I cannot recall a word in Mandarin, I tend to immediately produce it in English.

1      2      3      4      5

4. I sometimes do not realize when I switch the language during a conversation (e.g., from English to Mandarin) or when I mix the two languages; I often realize it only if I am informed of the switch by another person.

1      2      3      4      5

5. When I switch languages, I do it consciously and intentionally.

1      2      3      4      5

6. It is difficult for me to control the language switches I introduce during a conversation (e.g., from English to Mandarin).

1      2      3      4      5

7. There are situations in which I always switch between the two languages.

1      2      3      4      5

8. There are certain topics or issues for which I normally switch between the two languages.

1      2      3      4      5

9. Do you mix words or sentences from two languages in your own speech (e.g. saying a sentence in one language but use a word or phrase from another language in the middle of the sentence)?

Yes    No

10. I tend to say certain words in Mandarin when I'm speaking in English.

1      2      3      4      5

11. I tend to say certain words in English when I'm speaking in Mandarin.

1      2      3      4      5

12. I try to avoid switching between languages in conversation.

1      2      3      4      5

13. List the two or more languages that you mix with different people, and estimate the frequency of mixing in normal conversation, using a scale of 1-7, where 1 is 'Never', 4 is 'Sometimes', and 7 is 'Always.'

	Languages mixed	Frequency of mixing (1-7)
Family members		
Friends		
Classmates		
Co-workers		

#### D. Heritage speakers

1. Before starting school, what language did you *use* the most?

2. Before starting school, what language did you *hear* the most?

3. Before age 7, approximately what percent of the time were English, Mandarin, and other languages used in your home?

	Percent of time
<b>Mandarin</b>	
<b>English</b>	
<b>Other languages:</b>	
<b>TOTAL</b>	<b>= 100%</b>

4. Did you ever take or are you currently taking a heritage language course? A heritage language course is a language course for people who have learned the language from family but want to be formally educated in that language.

Yes

No

If yes, for how long?

5. How often do you visit your country of heritage?

a. Once every 3-5 years

b. Once every 2-3 years

c. Once a year

d. Twice a year

e. Three or more times a year

## Appendix E

Experiment 3 visual stimuli for English sentences. Mandarin words corresponding to images are in Pinyin, with English translations enclosed in parentheses.

Target	Cross-language Competitor	Within-language Competitor	Distractor
<i>English target</i>	<i>Mandarin cohort</i>	<i>English cohort</i>	<i>Distractor</i>
artichoke	ěrduǒ (ear)	arm	grapes
ball	bāo (bag)	box	lock
bee	bǐ (pen)	beans	candle
beetle	bīngxiāng (refrigerator)	beer	camel
bus	běn zi (notebook)	butterfly	turtle
cherry	qié zi (eggplant)	chair	suitcase
coat	kòu zi (button)	comb	vase
diamond	dàishǔ (kangaroo)	dice	glasses
goat	gǒu (dog)	gorilla	pig
lamp	lán zi (basket)	ladder	scissors
leaf	lí zi (pear)	leek	key
monkey	mén (door)	mushroom	fox
mountain	māo (cat)	mouse	bear
peach	pí bāo (purse)	pizza	fish
phone	fēngzhēng (kite)	fork	stove
pipe	pái (playing cards)	pineapple	accordion
shark	xiàng (elephant)	shovel	refrigerator
tie	tàiyáng (sun)	tiger	horse
tulip	tùzǐ (rabbit)	tombstone	raccoon
<i>Mandarin target</i>	<i>English cohort</i>	<i>Mandarin cohort</i>	<i>Distractor</i>
lán qiú (basketball)	lantern	lán bǎo shí (sapphire)	pot
shū (book)	shoe	shù (tree)	knife
píng zi (bottle)	pig	píng guǒ (apple)	alligator
miàn bāo (bread)	meat	miàn tiáo (noodles)	carrot
qì chē (car)	cheese	qí qiú (balloon)	onion
bēi zi (cup)	bagel	bèi zi (quilt)	umbrella
wá wa (doll)	watch	wà zi (sock)	toothbrush
shǒu tàò (glove)	soda	shǒu jī (cellphone)	kite
mào zi (hat)	mouse	mào jīn (towel)	flower
xīn (heart)	ship	xīng (star)	bowl
bào zi (leopard)	ball	bào zhǐ (newspaper)	rabbit
dēng pào (lightbulb)	duck	dèng zi (stool)	ant
dì tú (map)	deer	diàn shì (television)	drum
kǒng què (peacock)	coal	kǒng lóng (dinosaur)	lion
lǐ zi (plum)	leash	lǐ wù (gift)	corn
tāng (soup)	taco	táng guǒ (candy)	peach
sháo zi (spoon)	saw	shào zi (whistle)	tennis racket
xī hóng shì (tomato)	sheep	xī guā (watermelon)	eagle



*Experiment 3 visual stimuli for Mandarin sentences. Mandarin words corresponding to images are in Pinyin, with English translations enclosed in parentheses.*

<b>Target</b>	<b>Cross-language Competitor</b>	<b>Within-language Competitor</b>	<b>Distractor</b>
<i>English target</i>	<i>Mandarin cohort</i>	<i>English cohort</i>	<i>Distractor</i>
arm	ěrduǒ (ear)	artichoke	grapes
beans	bǐ (pen)	bee	candle
beer	bīngxiāng (refrigerator)	beetle	camel
box	bāo (bag)	ball	lock
butterfly	běn zì (notebook)	bubbles	turtle
chair	qíézi (eggplant)	cherry	vase
comb	kòu zì (button)	coat	suitcase
dice	dàishǔ (kangaroo)	diamond	glasses
fork	fēngzhēng (kite)	phone	glasses
gorilla	gǒu (dog)	goat	pig
ladder	lán zì (basket)	lamp	scissors
leek	lí (pear)	leaf	key
mouth	māo (cat)	mountain	bear
mushroom	mén (door)	monkey	fox
pizza	pí bāo (purse)	peach	fish
pineapple	pái (playing cards)	pipe	accordion
shovel	xiàng (elephant)	shark	hammer
tiger	tàiyáng (sun)	tie	horse
tombstone	tùzǐ (rabbit)	tulip	raccoon
<i>Mandarin target</i>	<i>English cohort</i>	<i>Mandarin cohort</i>	<i>Distractor</i>
píng guǒ (apple)	pig	píng zì (bottle)	alligator
qí qiú (balloon)	cheese	qì chē (car)	onion
táng guǒ (candy)	taco	tāng (soup)	peach
shǒu jī (cellphone)	soda	shǒu tàò (glove)	kite
kǒng lóng (dinosaur)	coal	kǒng què (peacock)	lion
lǐ wù (gift)	leash	lǐ zì (plum)	corn
bào zhǐ (newspaper)	ball	bào zì (leopard)	rabbit
miàn tiáo (noodles)	meat	miàn bāo (bread)	carrot
bèi zì (quilt)	bagel	bēi zì (cup)	umbrella
lán bǎo shí (sapphire)	lantern	lán qiú (basketball)	pot
wà zì (sock)	watch	wá wa (doll)	toothbrush
xīng (star)	ship	xīn (heart)	bowl
dèng zì (stool)	duck	dēng pào (lightbulb)	ant
diàn shì (television)	deer	dì tú (map)	drum
mào jīn (towel)	mouse	mào zì (hat)	flower
shù (tree)	shoe	shū (book)	knife
xī guā (watermelon)	sheep	xī hóng shì (tomato)	eagle
shào zì (whistle)	saw	shaó zì (spoon)	tennis racket

## Appendix F

*Experiment 3 auditory stimuli. Target words are underlined. Mandarin sentences have English translations below. Mandarin target words are in Pinyin, with English translations enclosed in parentheses.*

English sentences:

1. The young boy immediately saw the bee flying around the room.
2. Everyone suddenly noticed that the beetle had disappeared from the shelf.
3. She didn't realize that the boy really wanted to see the mountain.
4. John didn't realize that the lamp was no longer by the wall.
5. The teacher finally decided on a song that was about a goat.
6. He ignored the fact that there was a monkey crouching by the bushes.
7. She was baffled by the photo of the artichoke hanging on her wall.
8. The man was looking at the diamond as a suspicious clue.
9. The child continued eyeing the table so he could take the leaf.
10. They weren't very interested in the conversation about the shark.
11. They eventually decided that the tulip should be left on the piano.
12. We thought maybe the bus already left us behind.
13. The man contended that the coat was actually a valuable antique.
14. I was mildly confused about why the boy would have the pipe.
15. He walked into the room before noticing the picture of the cherry.
16. I noticed there was someone who was holding a ball.
17. The family kept thinking that the soldier would notice the phone.
18. They couldn't decide between the peach and the watermelon.
19. She was convinced that the puzzle solution focused on the tie.
20. We thought that it was confusing that a píng zi (bottle) could be talking to us.
21. The group of friends eventually found the xī hóng shì (tomato) back in the truck.
22. We didn't really think that we would find a mào zi (hat) in a tree in our yard.
23. He actually decided to bring the lán qiú (basketball) to the meeting with the stranger.
24. He refused to acknowledge that the shaó zi (spoon) could be an important clue.
25. She thought it might be good to have her bēi zi (cup) with her on the trip.
26. We never expected to have argued so much over a bào zi (leopard).
27. The last thing he did was prepare the miàn bāo (bread) for our meal.
28. The woman finally took the qì chē (car) with her to the garage.
29. I knew that in the end, the story would not mention a dì tú (map).
30. We were surprised that the key to the weird puzzle was a xīn (heart).
31. He explained with much confusion that the lǐ zi (plum) was in the box he carried.
32. It wasn't until an hour later that they saw there was a shū (book).
33. The last thing they wanted to eat was the tāng (soup).
34. I left the store having bought many random items including a wá wa (doll).
35. She went through too much trouble to ask her neighbor for just a shǒu tào (glove).
36. My sister told me that her least favorite drawing was of the kǒng què (peacock).
37. He flipped through the picture book for a long time looking for the dēng pào (lightbulb).

## Mandarin sentences:

38. Tā shuō kàn dào zhuō shàng de hézi li yǒu beans  
He said he saw that there were beans in the box on the table.
39. Wǒ kàn dào zázhì límian yǒu guānyú beer de jièshào  
I saw an article about beer in the magazine.
40. Wǒmen jīntiān xué de shēngcí bāokuò mouth  
The vocabulary that we learned today includes “mouth”
41. Wǒ zuótiān wèn línjū jièle ladder zhāi píngguǒ  
Yesterday, I asked my neighbor to borrow a ladder for picking apples.
42. Mèimei shuō dònghuà piàn lǐ de gorilla huì shuōhuà  
Little Sister said that the gorilla in the cartoon can talk.
43. Tā zài shùlín lǐ kàn dào qíguài de mushroom  
She saw a strange mushroom in the woods.
44. Tā yī jìn chúfáng jiù bǎ arm zhuàng daole  
When she walked in the kitchen, she hit her arm.
45. Tā zuótiān gěi wǒ kàn de diamond hěn piàoliang  
The diamond that he showed me yesterday is very pretty.
46. Zhuōzi shàng de leek shì línjū āyí liú gěi wǒ de  
The leek on the table is from the lady next door.
47. Wǒ wèn péngyǒu jièle yī běn hé shark yǒuguān de shū  
I asked my friend to borrow a book about sharks.
48. Tā zài huí jiā de lùshàng kàn dào lù biān yǒu tombstone  
He saw a tombstone on the side of the road on his way home.
49. Mèimei shuō tā fēicháng xǐhuān piàoliang de butterfly  
Little Sister said she loves butterflies.
50. Wǒ jīntiān zǎoshang chūmén de shíhòu wàngle bǎ coat chuān hǎo  
I forgot my coat when I left the house today.
51. Péngyǒu wèn wǒ xǐ bù xǐhuān pineapple  
My friend asked me whether or not I like pineapples.
52. Āyí bǎ gāng mǎi de chair fàng dào kètīng  
Aunt put the newly purchased chair in the living room.
53. Shìyǒu shuō fángjiān lǐ yǒu gè box shì gěi wǒ de  
My roommate told me there’s a box for me in our room.
54. Mèimei bù xiǎoxīn bǎ tā de fork diào dīshàngle  
Little Sister accidentally dropped her fork onto the floor.
55. Wǒ bǎ gānggāng mǎi lái de pizza fàng zhuōzi shàng  
I put the pizza that I just bought onto the table.
56. Wǒ mèimei huà de tiger déle yī děng jiǎng  
The tiger that my sister drew won the first prize.
57. Nà fú huà shàng de píngguǒ huà de hěn piàoliang  
The apple in the painting is very pretty.
58. Wǒ péngyǒu jiā hòuyuán lǐ de xīguā hěn dà  
The watermelons in my friend’s backyard are very big.
59. Wǒ ràng shìyǒu bǎ dīshàng de máo jīn jiē qǐ lái  
I asked my roommate to pick up their towels from the ground.

60. Jīnnián wǒ shēngri shōu dào le tā sòng de lánbǎoshí (sapphire)  
On my birthday this year, I received a sapphire from him.
61. Wǒ cóng dìshàng jiǎn qǐ le yīgè shàozǐ (spoon)  
I picked up a spoon from the floor.
62. Wǒ ràng tā bāng wǒ bǎ zhèxiē bèi zi (quilts) shōu qǐ lái  
I asked them to help me put these quilts away.
63. Tā shǒu lǐ de bào zhǐ (newspaper) hǎo xiàng shì zuótiān de  
The newspaper that he's holding seems to be from yesterday.
64. Fùjìn de shāngdiàn mài de miànbāo (bread) fēi cháng hào chī  
The bread from the neighborhood bakery is tasty.
65. Wǒmen zuótiān mǎi de qì qiú (balloons) hěn piàoliang  
The balloons we bought yesterday are very nice.
66. Wǒmen jīntiān kàn dào de diànshì (television) fēi cháng jiù  
The television that we saw today is rather old.
67. Mèimei huà de xīn (heart) bǐ wǒ huà de hǎo kàn  
The heart my little sister drew looks better than the one I drew.
68. Nǐ huí jiā zhīqián bié wàng bǎ tā de lǐwù (gift) fàng huí qù  
Don't forget to put away his gift before you leave.
69. Lǐ xiānshēng nǚ'ér de shù (trees) zhǎng dé hěn gāo  
Mr. Li's daughter's trees have grown very tall.
70. Wǒ juéde nǐ jīntiān chī de tángguǒ (candy) hái bùcuò  
The candy that you ate today is pretty good.
71. Wǒ bǎ mèimei de wàzi (socks) fàng zài zhuōzi shàng le  
I put Little Sister's socks onto the table.
72. Tā jīntiān chūqù wán de shíhòu wàngjì dài shǒujī (cellphone)  
He forgot his cellphone when he went out today.
73. Wǒjiā mén qián de shānshàng fāxiàn le kǒnglóng (dinosaur) de huàshí  
Dinosaur fossils were found on the hill in front of my house.
74. Tā bǎ jiālǐ de dèngzǐ (stool) rēng le chū qù  
He threw the stool out of the house.

**Appendix G***Experiment 3: Looks to Mandarin competitors in English sentences.*

	$\beta$	Std. Error	<i>t</i> value	Pr(>  <i>t</i>  )
1. (Intercept)	0.1224	0.0228	5.376	2.52e-06 ***
2. Linear polynomial	-0.3429	0.0677	-5.065	9.74e-06
3. Quadratic polynomial	0.0444	0.0329	1.347	0.1815
4. Cubic polynomial	0.0492	0.0330	1.489	0.1398
5. Switch – Yes	0.0716	0.0306	2.336	0.0257 *
6. Spliced – Identity	0.0116	0.0146	0.790	0.4309
7. Spliced – Cross	0.0090	0.0146	0.615	0.5394
8. BLP	-0.0015	0.0113	-0.129	0.8972
9. Lin:SwitchY	0.1755	0.0935	1.876	0.0695 .
10. Quad:SwitchY	-0.0639	0.0472	-1.352	0.1798
11. Cub:SwitchY	-0.0204	0.0475	-0.430	0.6684
12. Lin:SpliceI	-0.0110	0.0488	-0.224	0.8226
13. Lin:SpliceX	0.0520	0.0486	1.069	0.2863
14. Quad:SpliceI	-0.0151	0.0389	-0.388	0.6983
15. Quad:SpliceX	-0.0219	0.0387	-0.565	0.5724
16. Cub:SpliceI	0.0172	0.0384	0.448	0.6546
17. Cub:SpliceX	0.00461	0.0383	0.121	0.9041
18. SwitchY:SpliceI	-0.0306	0.0145	-2.109	0.0349 *
19. SwitchY:SpliceX	-0.0065	0.0140	-0.459	0.6462
20. Lin:BLP	0.0093	0.0349	0.265	0.7913
21. Quad:BLP	-0.0524	0.0274	-1.908	0.0572 .
22. Cub:BLP	0.0165	0.0265	0.635	0.5257
23. SwitchY:BLP	0.0110	0.0103	1.068	0.2856
24. SpliceI:BLP	-0.0029	0.0146	-0.200	0.8419
25. SpliceX:BLP	-0.0279	0.0145	-1.917	0.0573 .
26. Lin:SwitchY:SpliceI	0.0524	0.0573	0.913	0.3611
27. Lin:SwitchY:SpliceX	-0.0874	0.0556	-1.572	0.1159
28. Quad:SwitchY:SpliceI	-0.0051	0.0564	-0.090	0.9285
29. Quad:SwitchY:SpliceX	0.0123	0.0544	0.226	0.8211
30. Cub:SwitchY:SpliceI	-0.0349	0.0544	-0.642	0.5211
31. Cub:SwitchY:SpliceX	0.0243	0.0532	-0.456	0.6484
32. Lin:SwitchY:BLP	-0.0482	0.0407	-1.183	0.2367
33. Quad:SwitchY:BLP	-0.0166	0.0395	-0.420	0.6744
34. Cub:SwitchY:BLP	0.0191	0.0385	0.496	0.6198
35. Lin:SpliceI:BLP	-0.0280	0.0489	-0.573	0.5676
36. Lin:SpliceX:BLP	0.0159	0.0484	0.328	0.7429
37. Quad:SpliceI:BLP	0.0567	0.0389	1.457	0.1460
38. Quad:SpliceX:BLP	0.0689	0.0383	1.796	0.0733
39. Cub:SpliceI:BLP	-0.0115	0.0385	-0.298	0.7659
40. Cub:SpliceX:BLP	-0.0361	0.0379	-0.950	0.3425

41. SwitchY:SpliceI:BLP	0.0071	0.0144	0.488	0.6256
42. SwitchY:SpliceX:BLP	0.0280	0.0141	1.983	0.0474 *
43. Lin:SwitchY:SpliceI:BLP	0.1158	0.0572	2.024	0.0430 *
44. Lin:SwitchY:SpliceX:BLP	0.0091	0.0556	0.163	0.8705
45. Quad:SwitchY:SpliceI:BLP	-0.0088	0.0561	-0.157	0.8749
46. Quad:SwitchY:SpliceX:BLP	-0.0290	0.0543	-0.534	0.5933
47. Cub:SwitchY:SpliceI:BLP	-0.0414	0.0545	-0.760	0.4472
48. Cub:SwitchY:SpliceX:BLP	-0.0111	0.0531	-0.208	0.8352

Groups	Name	Variance	Std.Dev.	Corr.		
Subject:Splice	(Intercept)	2.889e-03	0.05375			
	ot1	2.316e-02	0.15217	-0.01		
	ot2	4.316e-03	0.06569	-0.33	-0.33	
	ot3	4.296e-03	0.065541	-0.21	-0.92	0.10
Subject	(Intercept)	1.106e-03	0.03325			
	ot1	3.217e-03	0.05671	-0.01		
	ot2	2.152e-05	0.04638	-0.56	-0.82	
	ot3	2.321e-05	0.00481	0.74	-0.68	0.13
Target	(Intercept)	6.665e-03	0.08163			
	ot1	5.606e-02	0.23676	0.74		
	ot2	5.445e-03	0.07378	-0.94	-0.89	
	ot3	5.642e-03	0.07511	-0.68	-0.99	0.82
Residual		1.1185e-01	0.34423			

**Appendix H***Experiment 3: Looks to English competitors in Mandarin sentences.*

	$\beta$	Std. Error	$t$ value	Pr(>  $t$  )
1. (Intercept)	0.1045	0.0125	8.345	2.25e-13 ***
2. Linear polynomial	-0.2689	0.0439	-6.115	8.60e-09
3. Quadratic polynomial	0.0673	0.0289	2.322	0.02161 *
4. Cubic polynomial	0.0565	0.0244	2.313	0.02167 *
5. Switch – Yes	0.0229	0.0137	1.671	0.10068
6. Spliced – Identity	0.0239	0.0117	2.043	0.04282 *
7. Spliced – Cross	-0.0014	0.0117	-0.127	0.89882
8. BLP	0.0030	0.0093	0.328	0.74326
9. Lin:SwitchY	-0.0575	0.0443	-1.296	0.19950
10. Quad:SwitchY	0.0057	0.0346	0.166	0.86848
11. Cub:SwitchY	-0.0043	0.0304	-0.142	0.88694
12. Lin:SpliceI	-0.1115	0.0503	-2.215	0.02818 *
13. Lin:SpliceX	-0.0300	0.0502	-0.599	0.55034
14. Quad:SpliceI	0.0227	0.0328	0.692	0.48941
15. Quad:SpliceX	0.0219	0.0327	0.671	0.50254
16. Cub:SpliceI	0.0182	0.0312	0.583	0.56025
17. Cub:SpliceX	-0.0095	0.0311	-0.307	0.75893
18. SwitchY:SpliceI	-0.0250	0.0098	-2.548	0.01084 *
19. SwitchY:SpliceX	-0.0167	0.0097	-1.720	0.08539 .
20. Lin:BLP	0.0475	0.0365	1.302	0.19476
21. Quad:BLP	-0.0304	0.0248	-1.223	0.22222
22. Cub:BLP	0.0178	0.0226	0.787	0.43151
23. SwitchY:BLP	-0.0312	0.0069	-4.504	6.71e-06 ***
24. SpliceI:BLP	0.0028	0.0118	0.237	0.81286
25. SpliceX:BLP	0.0114	0.0118	0.972	0.33281
26. Lin:SwitchY:SpliceI	0.1072	0.0388	2.761	0.00576 ***
27. Lin:SwitchY:SpliceX	0.0904	0.0384	2.351	0.01874
28. Quad:SwitchY:SpliceI	-0.0021	0.0384	-0.056	0.95505
29. Quad:SwitchY:SpliceX	-0.0255	0.0381	-0.668	0.50418
30. Cub:SwitchY:SpliceI	-0.0135	0.0383	-0.354	0.72366
31. Cub:SwitchY:SpliceX	-0.0145	0.0379	-0.383	0.70168
32. Lin:SwitchY:BLP	-0.0615	0.0274	-2.2240	0.02511 *
33. Quad:SwitchY:BLP	0.0375	0.0271	1.380	0.16757
34. Cub:SwitchY:BLP	-0.0091	0.0270	-0.337	0.73620
35. Lin:SpliceI:BLP	-0.0720	0.0506	-1.423	0.15671
36. Lin:SpliceX:BLP	-0.0625	0.0506	-1.234	0.21892
37. Quad:SpliceI:BLP	0.0108	0.0329	0.329	0.74246
38. Quad:SpliceX:BLP	0.0406	0.0329	1.232	0.21891
39. Cub:SpliceI:BLP	-0.0397	0.0313	-1.266	0.20644

40. Cub:SpliceX:BLP	-0.0595	0.0314	-1.894	0.05901 .
41. SwitchY:SpliceI:BLP	0.0079	0.0098	0.810	0.41819
42. SwitchY:SpliceX:BLP	0.0222	0.0097	2.274	0.02297 *
43. Lin:SwitchY:SpliceI:BLP	0.1121	0.0388	2.883	0.00394 **
44. Lin:SwitchY:SpliceX:BLP	0.0164	0.0385	0.427	0.66926
45. Quad:SwitchY:SpliceI:BLP	-0.0057	0.0385	-0.149	0.88160
46. Quad:SwitchY:SpliceX:BLP	-0.0362	0.0382	-0.949	0.34244
47. Cub:SwitchY:SpliceI:BLP	0.0401	0.0383	1.046	0.29544
48. Cub:SwitchY:SpliceX:BLP	0.0439	0.0380	1.155	0.24823

Groups	Name	Variance	Std.Dev.	Corr.		
Subject:Splice	(Intercept)	0.00203	0.04513			
	ot1	0.04056	0.20142	-0.89		
	ot2	0.00076	0.08730	0.29	-0.57	
	ot3	0.00555	0.07454	0.70	-0.60	-0.31
Subject	(Intercept)	0.00074	0.02725			
	ot1	0.00193	0.04401	0.86		
	ot2	0.00292	0.05404	-0.95	-0.65	
	ot3	0.00034	0.01868	-0.35	-0.79	0.04
Target	(Intercept)	0.00128	0.03590			
	ot1	0.01118	0.10577	0.05		
	ot2	0.00424	0.06516	-0.42	-0.58	
	ot3	0.00178	0.04227	0.15	-0.66	-0.21
Residual		0.08212	0.28657			

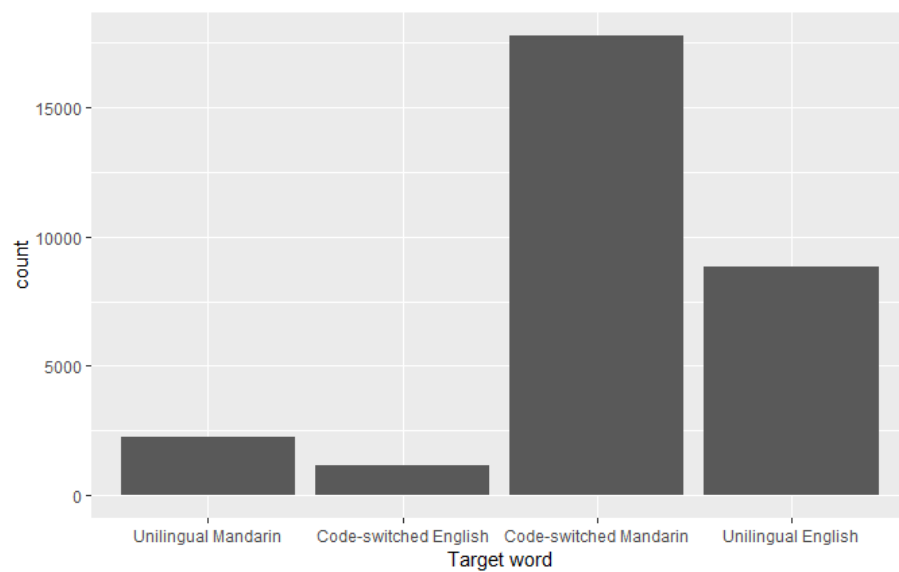


### Appendix I

The following table shows the number of trials for each target word where the corresponding image was not fixated upon after target onset in Experiment 3. Mandarin targets are in Pinyin with English translations in parentheses.

	Target	Unilingual or code-switch	# Trials where target not recognized
1	artichoke	Unilingual	3
2	lán qiú (basketball)	Code-switch	4
3	beetle	Unilingual	2
4	shū (book)	Code-switch	18
5	píng zi (bottle)	Code-switch	2
6	qì chē (car)	Code-switch	9
7	cherry	Unilingual	9
8	coat	Unilingual	3
9	comb	Code-switch	2
10	bēi zi (cup)	Code-switch	7
11	diamond	Unilingual	1
12	kǒng lóng (dinosaur)	Unilingual	5
13	wá wa (doll)	Code-switch	25
14	shǒu tào (glove)	Code-switch	10
15	goat	Unilingual	16
16	hat	Unilingual	6
17	xīn (heart)	Code-switch	17
18	ladder	Code-switch	1
19	lamp	Unilingual	1
20	leaf	Unilingual	20
21	leek	Code-switch	1
22	bào zi (leopard)	Code-switch	16
23	dēng pào (lightbulb)	Code-switch	25
24	dì tú (map)	Code-switch	11
25	peach	Unilingual	1
26	kǒng què (peacock)	Code-switch	13
27	phone	Unilingual	4
28	pipe	Unilingual	14
29	pizza	Code-switch	1
30	lǐ zi (plum)	Code-switch	4
31	lán bǎo shí (sapphire)	Unilingual	3
32	shark	Unilingual	1
33	shovel	Code-switch	4
34	sháo zi (spoon)	Code-switch	5
35	xīng (star)	Unilingual	10
36	tie	Unilingual	12
37	xī hóng shì (tomato)	Code-switch	3
38	tombstone	Code-switch	1
39	mào jīn (towel)	Unilingual	1
40	tulip	Unilingual	1
41	shào zi (whistle)	Unilingual	3

*The majority of these words occurred in English sentences, with the highest number of unrecognized targets occurring as Mandarin code-switches in English sentences.*



This plot shows the raw averaged fixation proportions to all four types of images (target, within-language competitor, cross-language competitor, and filler), for all trials for unrecognized targets in Experiment 3, where the image corresponding to the target word was not fixated upon after the target onset. These trials were included in the Experiment 3 analyses.

