

Short title: Linking frequency to switch costs

Full title: Linking frequency to bilingual switch costs during real-time sentence comprehension

Lauren K. Salig

<https://orcid.org/0000-0002-9394-9033>

Program in Neuroscience and Cognitive Science

University of Maryland, College Park

Jorge R. Valdés Kroff

<https://orcid.org/0000-0002-3943-5496>

Department of Spanish and Portuguese Studies

University of Florida

L. Robert Slevc

<https://orcid.org/0000-0002-5183-6786>

Department of Psychology

Program in Neuroscience and Cognitive Science

University of Maryland, College Park

Jared M. Novick

<https://orcid.org/0000-0001-9528-8972>

Department of Hearing and Speech Sciences

Program in Neuroscience and Cognitive Science

University of Maryland, College Park

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Address for correspondence:

Lauren Salig

lsalig@umd.edu

University of Maryland, Biology/Psychology Building, Room 3150,

4094 Campus Dr., College Park, MD 20742

Abstract

Bilinguals experience processing costs when comprehending code-switches, yet the magnitude of the cost fluctuates depending on numerous factors. We tested whether switch costs vary based on the frequency of different types of code-switches, as estimated from natural corpora of bilingual speech and text. Spanish-English bilinguals in the U.S. read single-language and code-switched sentences in a self-paced task. Sentence regions containing code-switches were read more slowly than single-language control regions, consistent with the idea that integrating a code-switch poses a processing challenge. Crucially, more frequent code-switches elicited significantly smaller costs both within and across most classes of switch types (e.g., within verb phrases and when comparing switches at verb-phrase and noun-phrase sites). The results suggest that, in addition to learning distributions of syntactic and semantic patterns, bilinguals develop finely tuned expectations about code-switching behavior—representing one reason why code-switching in naturalistic contexts may not be particularly costly.

Key Phrases

code-switching types

comprehension

statistical learning

switch costs

bilingualism

Linking frequency to bilingual switch costs during real-time sentence comprehension

Bilingual speakers and writers sometimes switch from one language to another within a single sentence, known as intrasentential code-switching (Poplack, 1980). Code-switching is relatively common (Beatty-Martínez & Dussias, 2017; Guzzardo Tamargo et al., 2016; Poplack, 1980), which may be surprising given that it can induce significant processing costs (Beatty-Martínez et al., 2018; Valdés Kroff et al., 2018; Van Hell et al. 2018). For example, during comprehension, bilinguals take longer to read code-switched regions of a sentence (e.g., Bultena et al., 2015) and have longer first-fixation durations on code-switched words as compared to single-language equivalents, suggesting difficulty in the initial processing of linguistic input that switches languages mid-utterance (e.g., Altarriba et al., 1996).

Why is bilinguals' processing of code-switches costly? One hypothesis is that, while comprehending a sentence, a code-switch brings linguistic representations into direct conflict (Adler et al., 2020; Wu & Thierry, 2013). Consider (1):

(1) “La electricista tiene la box with her tools.” [*The electrician has the box with her tools.*] (adapted from Johns et al., 2019)

During sentence processing, readers and listeners make parsing commitments as linguistic input is perceived incrementally, and even predictively (Altmann & Kamide, 1999), guided by phonological, syntactic, semantic, and discourse-level cues to interpretation (e.g., Boland & Blodgett, 2001; Chambers et al., 2002; Trueswell et al., 1994). Upon encountering the feminine determiner “la,” bilingual comprehenders may form expectations about the upcoming input—e.g., Spanish phonology, a feminine Spanish noun, or perhaps just Spanish in general based on the speaker’s identity (Beatty-Martínez & Dussias, 2019). The arrival of the English word “box” may conflict with their expectations, and the resolution of this conflict may reflect a

switch cost. Findings from language processing studies support this interpretation: Bilinguals increase their engagement of cognitive control—a mechanism that assists in conflict resolution (Botvinick et al., 2001)—when reading code-switched sentences or when exposed to mixed-language environments (Adler et al., 2020; Wu & Thierry, 2013). A reasonable inference then is that switch costs are indicative of a representational conflict in sentence processing that takes time to resolve.

However, switch costs can be attenuated under supporting contexts (Beatty-Martínez et al., 2018; Guzzardo Tamargo et al. 2016) and in fact are not always found (Gullifer et al., 2013; Johns et al., 2019; Moreno et al., 2002). Some suggest that bilinguals experience no switch costs when code-switches are naturalistic and appropriate in a particular social situation (Beatty-Martínez et al., 2021; Johns et al., 2019; Moreno et al., 2002). Bilinguals also regularly produce and understand code-switches naturally without suffering any serious impediment to communication (e.g., Poplack, 1980). Yet the reasons underlying why switch costs emerge to varying degrees across studies remains an open question. One reason may be that processing demands differ by the grammatical categories involved at the switch: Certain code-switches may involve lessened or even no representational conflict, and thereby elicit decreased costs than other switch types. The purpose of the current study is to investigate factors that modulate the magnitude of switch costs across a broad range of switch types, to better understand when and why costs emerge.

Linking Production Patterns to Switch Costs during Comprehension

The extent to which integrating code-switches in comprehension generates cross-language competition—which in turn may lead to measurable switch costs—likely depends on

many cognitive, linguistic, and social factors. For example, returning to the code-switched phrase in Sentence (1), the English noun “box” is preceded by the Spanish article “la,” which encodes for feminine grammatical gender. In U.S. Spanish-English bilingual communities, it is common to find English nouns preceded by the Spanish article “el” instead. Interestingly, “el” marks for masculine grammatical gender, thus potentially creating cross-linguistic conflict because the Spanish translation equivalent for “box” is the Spanish feminine noun “caja.” Despite this potential conflict, these mixed Spanish-article English-noun constructions are among the most common code-switch types in Spanish-English bilingual speech (Poplack, 1980). Consequently, for bilinguals in the U.S., these code-switches might not seem implausible and thus may generate relatively little conflict across linguistic representations.

Indeed, research indicates that context and rates of exposure matter: The ease with which code-switches are processed varies on the basis of an individual’s code-switching experience (Beatty-Martínez & Dussias, 2017), the language background of others in the interaction (Kaan et al., 2020), and the type of code-switch itself (Beatty-Martínez & Dussias, 2017; Guzzardo Tamargo et al., 2016). However, the overarching factors that determine switch-cost magnitude are still being mapped out. While code-switch type can affect switch costs, prior work focuses primarily on within-category comparisons (e.g., switches within the noun phrase: masculine vs. feminine noun phrases, Beatty-Martínez & Dussias, 2017; adjective-noun vs. noun-adjective, Vaughan-Evans et al., 2020; switches within the verb phrase: progressive auxiliary verbs vs. perfective auxiliary verbs, Guzzardo Tamargo et al., 2016). What exactly makes one code-switch more difficult to process than another? Is there a parsimonious explanation to describe the general switch-cost patterns for the many types of code-switches that bilinguals confront?

Here, we examine the idea that exposure to certain types of switches in production makes them easier to integrate during comprehension, owing to increased experience: Switches like “el box” may be easier to process for code-switching bilinguals in the U.S. who hear or read this type of code-switch frequently. More generally, the reason why bilinguals are exposed more to certain types of switches than others may originate from production-based demands that cause certain types of switches to be more or less commonly produced, leading to asymmetrical distributions of code-switch types. Outside the domain of code-switching, this notion has been formalized as the Production-Distribution-Comprehension (PDC) model (MacDonald, 2013), which posits that demands on production increase the frequency of certain constructions over others, thereby adjusting rates of exposure that affect comprehension: More frequent constructions become easier to understand than less frequent ones.

Applying the PDC Model to the Comprehension of Code-switches

We start by evaluating why we might observe asymmetrical distributions of code-switches in production within the PDC framework. Consider MacDonald’s proposal that production is partially guided by organizing easier elements in an utterance first (easy-first principle). Code-switches are likelier to appear later in a prosodic unit (Johns & Steuck, 2021), which may indicate that code-switches are intentionally associated with more difficult content to be expressed (e.g., lower frequency words, Tomić & Valdés Kroff, 2022) or that they are used as a discursive strategy by the speaker to switch into a more readily accessible language. A second principle is the use and reuse principle, in which speakers are likely to repeat aspects of prior productions, such as how speakers are likely to reuse the syntactic structure of earlier utterances (i.e., structural priming; Bock, 1986). However, code-switching itself is not overtly produced

material or a particular syntactic structure, but rather a point at which language choice changes. Thus, extending this principle to code-switching suggests that speakers may prefer to code-switch at similar syntactic junctures (i.e., between a determiner and noun), which accumulate into predictable distributions over time. In a series of studies using a structural priming methodology, Kootstra and colleagues demonstrated that naïve participants are more likely to produce a code-switch immediately after a confederate has code-switched and when lexical and structural factors such as cognate status and word order are congruent across bilinguals' languages (Kootstra et al., 2010, 2012, 2020). Similarly, Fricke and Kootstra (2016) examined a Spanish-English bilingual corpus and found that preceding utterances that contain a code-switch are more likely to predict a code-switch in a current utterance. Of course, not all patterns of code-switches in production can be explained by production demands, which becomes apparent when we consider that different bilingual populations display different code-switching behaviors (e.g., Beatty-Martínez, Navarro-Torres, Dussias, Bajo, et al., 2020; Blokzijl et al., 2017; Poplack, 1988).

Critically, the PDC model also posits that comprehenders can use their exposure to production distributions to guide real-time processing: They track the regularity and frequency of various grammatical constructions that speakers produce, and less regular ones become easier to process with greater experience (e.g., Wells et al., 2009). For example, object-extracted relative clauses such as "*the man that the woman hugged*" have a distinctive word order and are generally less frequently produced as compared to subject-extracted relative clauses, e.g., "*the man that hugged the woman*." Consequently, subject-extracted relative clauses are generally easier to process in comprehension (Gennari & MacDonald, 2009), but increased exposure to relative clauses overall increases sensitivity to the (ir)regularity of syntactic forms (Wells et al.,

2009). Similarly, the statistical regularities of different types of code-switches may support learning over time, where more commonly produced switch types elicit less conflict and thus decrease processing difficulty. Rates of exposure to bilingual production patterns would therefore modulate the apparent costs associated with integrating code-switches during comprehension.

It is unclear though if the logic of the PDC model applies to bilinguals' comprehension of code-switches. Is the syntactic juncture at which a switch occurs the type of statistical information that people track? Moreover, the PDC model was formulated to explain how alternative syntactic structures are processed. A code-switched word or phrase often maintains the same meaning and lexical properties as a more expected word or phrase that continues in the same language, and in many cases code-switching may not alter the syntactic structure in any way, especially in typologically close languages. It is thus an open issue whether the PDC model can accommodate code-switching patterns, namely whether bilingual comprehenders implicitly exploit the statistics of sentence production distributions that differ only in the languages used, and not necessarily in meaning or sentence structure.

If the PDC model applies to the comprehension of code-switches, we would expect smaller switch costs during comprehension of code-switch types that are more frequent in production. Past studies have provided preliminary evidence that switch-cost magnitude in comprehension aligns with corpus patterns of switch types in production. In an electroencephalography (EEG) study, individuals with frequent code-switching experience demonstrated a larger late positive component (LPC)—indicating more integration difficulty—for uncommon feminine determiner-noun switches as compared to masculine ones (Beatty-Martínez & Dussias, 2017). Similarly, eye-tracking studies indicate that more frequent code-

switches within verb phrases are easier to comprehend than less frequent ones (Dussias et al., 2014; Guzzardo Tamargo et al., 2016; Valdés Kroff et al., 2018).

However, these studies each narrowly focus on a single class of code-switch (e.g., switches in noun *or* verb phrases) without comparing switch types in different categories, limiting the conclusions that can be drawn and perhaps strongly skewing the production distributions *within* the experiments. It is difficult then to determine if the PDC model explains switch costs outside of specific paired comparisons, particularly both across and within categories of switches at noun and verb sites. In fact, there are currently no sentence processing studies that compare costs for switches in noun and verb phrases (but see Ng et al., 2014; Rossi et al., 2021). Thus, there remain open questions about how broadly the PDC model applies to the comprehension of code-switches, as well as questions about how other factors might influence switch-cost magnitude.

If the PDC model does not apply to the comprehension of code-switches, then we expect that switch costs will not vary consistently based on production patterns found in corpora. In this case, more specific contextual factors may drive most of the variation in switch costs. Although the PDC model allows for other factors—such as the comprehender’s expectations for a specific interaction or the speaker’s attempts to tailor their speech to their audience—to play a role in modulating the ease of comprehension, the model highlights frequency in production as a more important factor. If production frequency is not a crucial ingredient, then we expect contextual factors such as the topic of conversation, the specific sentence’s context, or the identity of the interlocutor (e.g., Kaan et al., 2021) to play a large part in determining switch-cost magnitude. Moreover, prior work suggests that the relative engagement status of cognitive control—whether it is in a stronger or weaker state—can dynamically affect language processing. For example,

listeners revise their misinterpretations of temporarily ambiguous sentences faster when cognitive control has been experimentally upregulated (Hsu & Novick, 2016; Hsu et al., 2021; see also Ovans et al., 2022). The state of cognitive control in a particular interaction may also impact the comprehension of code-switches (see Salig et al., 2021 for a discussion). Here, we test how such contextual and cognitive factors impact switch-cost variation apart from more general distribution learning.

The Present Study

The overall goal of this study is to characterize the factors that influence processing costs associated with bilingual language comprehension, in particular to: 1) determine if distributions in production can predict processing ease, and 2) identify cognitive and language experience factors that might additionally modulate switch costs.

To address the first objective, Spanish-English bilinguals read single-language sentences or sentences that code-switched from Spanish to English in a noun or a verb phrase. Bilinguals read at their own pace in a task administered remotely via the internet, allowing us to calculate the difference in time spent reading code-switched regions as compared to single-language equivalents—for instance, how much longer it takes to read “la box” as compared to “the box” or “la caja.”

We predicted that, consistent with the PDC model, more frequent switch types should generate smaller switch costs compared to less common types. To make specific predictions, we examined corpora of Spanish-English bilingual language use. As can be seen in Figure 1, masculine determiner-noun code-switches like “el soap” are more common than feminine ones like “la box” (Beatty-Martínez & Dussias, 2017, Valdés Kroff, 2016). Progressive tense verb-

phrase switches (e.g., “mis amigos están cooking”) are more common than perfective ones (e.g., “mis amigos han cooked”); perfective tense verb-phrase switches at the auxiliary location (e.g., “mis amigos have cooked”) are more common than perfective tense verb-phrase switches at the participle location (e.g., “mis amigos han cooked,” Guzzardo Tamargo et al., 2016); and noun phrase code-switches are more common than verb phrase code-switches (Poplack, 1980). Note that these distributions were drawn from corpora of both verbal and written language when possible. Thus, smaller costs should emerge generally for a range of more frequently produced, and thus more commonly experienced, types of code switches. Based on data from corpora of bilingual language use, our hypotheses are:

1. Masculine determiner-noun switches (e.g., “el soap”) will be easier to process (have smaller switch costs) than feminine determiner-noun switches (e.g., “la box”).
2. Perfect tense switches at the auxiliary location (e.g., “mis amigos have cleaned”) will be easier to process than perfect tense switches at the participle location (e.g., “mis amigos han cleaned”).
3. Progressive tense switches (e.g., “mis amigos están/are cleaning”) will be easier to process than perfect tense switches (e.g., “mis amigos han/have cleaned”) at both the participle and the auxiliary location.
4. Mixed noun-phrase switches (switch at the noun) will be easier to process than mixed verb-phrase switches (switch at the participle).

<Insert Figure 1 about here>

Alternatively, if the PDC model does not apply to the comprehension of code-switches, then we would expect no variation in switch costs based on production frequency, suggesting that immediate contextual factors may play a much larger role in switch-cost magnitude than longer-term learning. To preview our results, we find that the PDC model explains variation in switch costs but may not alone capture the full picture of factors at play in the comprehension of code-switches—offering a novel contribution to the literature on how production and comprehension interact in code-switch processing.

For the second objective, we were interested in whether switch costs are modulated by factors beyond switch type, specifically code-switching experience and exposure to each language. To capture exposure to each language, we calculated a language entropy measure (Gullifer & Titone, 2020) based on percent of daily exposure to each language; higher language entropy indicates more balanced exposure. We made the exploratory prediction that:

5. Individual language experience, defined as code-switching experience and language entropy, will modulate switch costs.

Additionally, we expected that a bilingual's cognitive state at the time of reading a code-switch—particularly their relative engagement of cognitive control—might affect switch costs. Recall that, on one account, switch costs derive from conflict between the code-switched input and listeners' expectations. Past work demonstrates that bilinguals increase cognitive control in code-switched or mixed-language contexts (Adler et al., 2020; Wu & Thierry, 2013), presumably to help them resolve the conflict that a code-switch presents. Given that code-switches seem to require conflict resolution operations, we asked if bilinguals might process code-switches more easily (i.e., have reduced switch costs) if their state of cognitive control engagement was

experimentally increased before reading the code-switch (Hsu & Novick, 2016; Hsu et al., 2021; Ovans et al., 2022; Thothathiri et al., 2018).

To address this, bilinguals completed trials from a Flanker task before reading our critical sentences. On incongruent Flanker trials, participants indicated the direction of a central arrow despite flanking arrows pointing in a conflicting direction; these trials are known to increase cognitive control compared to congruent trials in which the central and flanking arrows point in the same direction and thus do not involve conflict (Eriksen & Eriksen, 1974; Gratton et al., 1992). Therefore, we predicted that:

6. Experimentally increasing cognitive control engagement with an incongruent Flanker trial will assist processing of an immediately subsequent code-switch (i.e., result in a smaller switch cost).

Method

This study was pre-registered. The materials, pre-registered analysis plan, R script used for analysis, and data from participants who consented to data sharing are available on OSF (<https://osf.io/5yzna/>).

Participants

152 self-identified Spanish-English bilinguals participated in the study online using their own devices and received class credit or entry into a gift card drawing as compensation. 45 people were excluded from data analysis based on pre-registered exclusion criteria: scoring less than 80% on comprehension questions, having accuracy lower than 50% on Flanker trials, and/or scoring lower than 30% on a grammar assessment. An additional 6 participants were excluded

due to a recording error. A total of 101 bilinguals (86 female, 15 male) were included in data analysis. 59% of the bilinguals learned Spanish before English, but on average, they reported being exposed to English more frequently in their daily lives. Additional participant characteristics are shown in Table 1. Overall, questionnaire responses suggest that the sample consists of relatively balanced bilinguals who may be slightly English dominant.

<Insert Table 1 around here>

Materials & Design

Participants completed the experiment remotely on pcIBEX (Zehr & Schwarz, 2018). In the experiment, we pseudorandomly interleaved Flanker arrow trials with self-paced reading sentence trials. After completing the experimental task, participants completed the language history questionnaire and grammar assessments on Qualtrics.

Sentence Stimuli

We included 96 critical sentences: half were code-switched and half were in a single-language—either English or Spanish depending on their randomly assigned list. 48 of the critical sentences involved a determiner-noun code-switch or single-language equivalent and 48 involved a verb-phrase code-switch or single-language equivalent. Table 2 outlines the distribution of sentence types. All code-switches were from Spanish to English to align with typical code-switching practices in the U.S. (Beatty-Martínez & Dussias, 2017; Blokzijl et al., 2017). Determiner-noun stimuli were a subset of materials found in Adler et al. (2020) and Johns et al. (2019). Within our materials, the determiner gender always agreed with the gender of the

noun in Spanish: We included switches like “la box” (Spanish translation equivalent: “la caja”) and “el soap” (Spanish translation equivalent: “el jabón”), but not “el box.” Verb stimuli were a subset of materials found in Adler et al. (2020) and Guzzardo Tamargo et al. (2016). We also included 72 filler sentences from Adler et al. (2020). Of these, only 8 contained code-switches so that 33% of all sentence stimuli in the experiment contained code-switches, which approximates observed rates of code-switching in U.S. bilinguals (Beatty-Martínez, Navarro-Torres, & Dussias, 2020; Johns et al., 2019; Piccinini & Arvaniti, 2015; Torres Cacoullos & Travis, 2018).

<Insert Table 2 about here>

Flanker Trials

There were 96 critical Flanker trials (48 congruent, 48 incongruent) as well as 112 filler Flanker trials (85 congruent, 27 incongruent). Flanker stimuli showed a central arrow in the middle of the screen flanked by two arrows on each side. On congruent trials, the flanking arrows pointed in the same direction as the center arrow. On incongruent trials, the flanking arrows pointed in the opposite direction as the center arrow. Participants were instructed to press the “J” key if the central arrow was pointing right and the “F” key if the central arrow was pointing left.

Comprehension Questions

A yes/no comprehension question followed all 96 critical sentences and 18 of the filler sentences. Questions tested attention to main ideas in the sentences. For example, the question for Example (1) above (repeated here: “La electricista tiene la box with her tools”) was: “Are the

tools in a bag?” (No). Questions were adapted from prior studies (Adler et al., 2020; Johns et al., 2019) or written by the first author. Participants were instructed to press the “J” key to answer yes and the “F” key to answer no, with response key reminders visible on screen.

Interleaved Flanker-Sentence Trial Sequences

The 96 critical trial sequences started with a Flanker trial, followed by a sentence trial, followed by a comprehension question. We also pseudorandomly interleaved 112 filler Flanker trials and 72 filler sentences (18 of which were followed by filler comprehension questions) to create additional sentence-to-Flanker, sentence-to-sentence, Flanker-to-Flanker, and Flanker-to-sentence pairings to discourage participants from strategically predicting upcoming trial type.

There were 8 fixed-order lists: Each list contained 24 congruent Flanker-unilingual sentence, 24 congruent Flanker-code-switched sentence, 24 incongruent Flanker-unilingual sentence, and 24 incongruent Flanker-code-switched sentence trial pairs, and list number determined the condition for any given Flanker-sentence pair. For each list, the default language was either Spanish or English and this determined the language of unilingual sentences and comprehension questions. To create the fixed-order for presentation, the 96 critical trial pairs were split into two experimental blocks and their order randomized within each block; then, filler trials were inserted.

Procedure

Within the experiment, each stimulus (sentence, Flanker, or comprehension question) was preceded by a 500-ms fixation cross with a 100-ms inter-stimulus interval between stimuli. Sentence trials were presented using a self-paced moving window paradigm in which

participants saw one word at a time with the others masked with dashes (Just et al., 1982).

Participants used the spacebar to advance through the sentence, re-masking all previous words as they advanced.

Participants read code-switched instructions, completed a 15-trial practice block, and then completed the interleaved experimental trials in two blocks, with a short break in between. After completing the second block, participants completed a demographic and language history questionnaire followed by two grammar assessments that were presented in random order. The grammar assessments were shortened 20-question versions of those used in Adler et al. (2020) (English Language Institute, 2001; Ministry of Education, Culture, and Sport of Spain, 2006).

The experiment took about one hour to complete.

Data Analysis

The regression models used to analyze the data were pre-registered before data collection. After applying participant exclusion criteria, individual trial exclusion criteria were applied before analysis. Sentence trials were excluded from analysis if: the prior Flanker response was inaccurate, the prior Flanker response time was more than 2.5 standard deviations away from that participant's mean, and/or the reading time in the region of interest was more than 2.5 standard deviations away from the participant's mean. At least 85% of trials were included in each analysis.

For each hypothesis (except the hypothesis about the effect of individual language experience, which is exploratory), we pre-registered analyses in four regions of interest pictured in Figure 2: the critical word (the switch or single-language equivalent), the word after, the second word after, and the combined 3-word region. When analyzing verb phrases alone, the

auxiliary-participle 2-word verb phrase was treated as the critical word. When comparing noun-to verb-phrase switches, only participle-location verb switches were included to allow for a comparison of 3-word regions where the switch occurs at a content word. For brevity, we report only results analyzing the combined 3-word critical region (or 4-word region in the case of verb-only analyses), although all results reported as significant survive a Bonferroni correction for four analyses for each hypothesis. Results in the individual word regions largely align with the combined region analyses, although switch effects generally tapered off by the second word after the switch.

<Insert Figure 2 around here>

Linear mixed-effects models were run using the *lme4* package (Bates et al., 2015), and p-values were approximated via the Satterthwaite degrees of freedom method with the *lmerTest* package in R (Kuznetsova et al., 2017), with the predicted variable as the region's logged reading time. All models included crossed random effects for participant and item number; models that did not converge were simplified using pre-registered criteria. Two-level factors were contrast coded as -0.5 and +0.5. Centered word length (in characters) was included as a covariate in models. Marginal R^2 values were extracted with the *MuMIn* R package (Barton, 2020), and effect sizes were extracted with the *sjstats* R package (Lüdecke, 2020).

Results

Participants had high overall accuracy on Flanker trials ($M=0.89$, $SD=0.31$) and on comprehension questions ($M=0.91$, $SD=0.29$), indicating that they were paying attention during the experimental tasks.

Switch Cost Effects

Switches at Noun Sites

We predicted that noun switches with masculine determiners would have smaller switch costs than ones with feminine determiners because of their higher frequency in corpora. As can be seen in Figure 3 and Table 3, there were switch costs for noun switches, but masculine switches seemed to elicit similar switch costs as feminine switches, counter to our prediction. A mixed-effect model predicting logged reading time of the 3-word region of critical noun stimuli confirmed these observations, with a main effect of sentence type ($\beta=-0.03$, $\eta_p^2=0.10$, $p<0.01$), but no main effect of the determiner's grammatical gender ($p=0.99$, $\eta_p^2<0.01$) and no interactions involving grammatical gender ($p\geq0.60$, $\eta_p^2<0.01$; model marginal $R^2=0.08$). The model included fixed effects for sentence type (code-switched or single-language), determiner grammatical gender (masculine or feminine), and default language (single-language sentences in English or in Spanish).

The model also revealed a two-way interaction between default language and sentence type ($\beta=0.12$, $\eta_p^2=0.22$, $p<0.01$) and a main effect of default language ($\beta=0.18$, $\eta_p^2=0.12$, $p<0.01$). Figure 4 demonstrates the interaction: Overall, reading speeds were much faster for the English default language, and there is a clear switch cost only for the English default language. Indeed, exploratory analysis revealed a significant switch cost when comparing code-switches to

English-only sentences, but no switch cost when comparing code-switches to Spanish-only sentences. Given that all code-switches were from Spanish to English, the lack of difference between code-switched and Spanish-only conditions may reflect a switch cost in itself, as the switch temporarily negated bilinguals' faster English reading ability, a point which we return to in the Discussion. The character length covariate was also significant in the model ($\beta < 0.01$, $\eta_p^2 = 0.02$, $p < 0.01$).

<Insert Figure 3 around here>

<Insert Table 3 around here>

<Insert Figure 4 around here>

Switches at Verb Sites

Based on corpora analyses, we predicted that perfect tense switches would have a smaller switch cost at the auxiliary location (e.g., “los editores have approved”) than at the participle location (e.g., “los modelos han signed”) and that progressive tense switches would have smaller switch costs than perfective tense switches. One model was run on critical verb stimuli to address these hypotheses, with logged 4-word region (auxiliary, participle, and the two subsequent words) reading time as the predicted variable. Fixed effects included sentence type, verb tense (progressive or perfective), switch location (auxiliary or participle), and default language, along with centered region length as a covariate.

There were no interactions including both verb tense and switch location ($p \geq 0.13$, $\eta_p^2 < 0.02$; model marginal $R^2 = 0.09$), so we consider each factor individually. As before, the model showed main effects of default language ($\beta = 0.19$, $\eta_p^2 = 0.10$, $p < 0.01$), sentence type ($\beta = -$

$0.03, \eta_p^2=0.06, p=0.01$), and their interaction ($\beta=0.17, \eta_p^2=0.41, p<0.01$). Here, exploratory analysis of the two-way interaction again showed a switch cost in the English default language but a switch benefit in the Spanish default language, as reading sped up quickly upon the switch to English. The character length covariate was significant ($\beta<0.01, \eta_p^2=0.01, p<0.01$).

Verb Switch Tense. As can be seen in Figure 5 and Table 4, progressive tense switches seem to elicit a smaller switch cost than perfective tense switches, in line with our prediction. The model confirmed this observation as verb tense interacted with sentence type ($\beta=0.03, \eta_p^2=0.03, p=0.01$); there was no main effect of verb tense ($p=0.82, \eta_p^2<0.01$). Exploratory analysis showed that the interaction followed the predicted pattern: Progressive tense switches had no significant switch cost, while perfective tense switches did have a significant switch cost.

<Insert Figure 5 around here>

<Insert Table 4 around here>

Verb Switch Location. Figure 6 and Table 5 show that participle switches appeared to elicit much larger costs than auxiliary switches, which seem to elicit no cost at all. The model confirmed that switch location interacted with sentence type ($\beta=-0.06, \eta_p^2=0.12, p<0.01$); there was no main effect of switch location ($p=0.08, \eta_p^2=0.06$). Exploratory analysis showed that the interaction was in the predicted direction: Switches at the auxiliary location had no significant switch cost, while switches at the participle location did. However, this interaction applied for both perfective and progressive code-switches, not just for perfective tense switches as we predicted.

<Insert Figure 6 around here>

<Insert Table 5 around here>

Comparing Noun and Verb Switch Sites

Given their higher frequency in production, we predicted that noun switches would have smaller switch costs than verb switches. Figure 7 and Table 6 show that noun switches did indeed seem to elicit smaller switch costs than verb switches, at least in the English default language; in the Spanish default language, there appear to be no switch costs. The model predicting logged 3-word reading time for nouns and participle-location verbs confirmed this observation. There was a three-way sentence type by default language by code-switch type interaction ($\beta=0.07$, $\eta_p^2=0.08$, $p<0.01$). Exploratory analysis indicated that in the English default language, there were switch costs, and switch costs were larger for verb switches than noun switches. In the Spanish default language, there were no switch costs or any reading difference for nouns as compared to verbs. This is in line with the results described above in which switch cost effects are washed out in the Spanish default language due to faster English reading.

The model's fixed effects included sentence type, code-switch (noun or verb) type, and default language, along with centered region length in characters as a covariate. In addition to the three-way interaction described above, there was a sentence type by default language two-way interaction ($\beta=0.16$, $\eta_p^2=0.34$, $p<0.01$; model marginal $R^2=0.08$), a main effect of sentence type ($\beta=-0.04$, $\eta_p^2=0.11$, $p<0.01$), a main effect of default language ($\beta=0.18$, $\eta_p^2=0.11$, $p<0.01$), and an effect of character length ($\beta=0.01$, $\eta_p^2=0.02$, $p<0.01$). There was no main effect of code-switch type (noun vs. verb; $\beta=-0.06$, $\eta_p^2=0.04$, $p=0.06$).

<Insert Figure 7 around here>

<Insert Table 6 around here>

Language Experience

We predicted that individual language experience would affect switch costs. As an exploratory analysis, we re-ran the three models with two additional language experience factors included in each: (1) code-switching experience, averaged across four self-rating questions on a 5-point scale, and (2) language entropy. Language entropy captures individuals' daily language diversity and was calculated using the `languageEntropy` package (Gullifer & Titone, 2020) by inserting the fraction of time that the bilinguals reported exposure to English, Spanish, and if applicable, another language. A higher language entropy value indicated more balanced exposure: An individual exposed to English 50% of the time and to Spanish 50% of the time would receive an entropy score of 1, while an individual exposed to English 100% of the time would receive an entropy score of 0. Since participants could indicate exposure to English, Spanish, and other languages, the maximum entropy score possible was 1.58 (or $\log_2(3)$ given three language choices), if a participant's exposure was split equally between three languages. Because these models were exploratory, we used a p-value threshold of 0.05.

In the model comparing masculine and feminine determiner-noun switches, there were no significant effects including code-switching experience or language entropy (model marginal $R^2=0.11$).

In the model comparing different types of verb code-switches, there was a three-way interaction between sentence type, switch location (at the participle vs. auxiliary), and language

entropy ($\beta=0.46$, $\eta_p^2<0.01$, $p=0.03$; model marginal $R^2=0.12$). There were no significant effects of code-switching experience. Using the interactions package (Long, 2019) to explore further, it seemed that as language entropy increased (exposure became more balanced), reading times became faster, and this was particularly true for code-switches at the participle location.

In the model comparing noun and verb code-switches, there was a three-way interaction between sentence type, code-switch type (noun vs. verb), and language entropy ($\beta=0.43$, $\eta_p^2=0.05$, $p=0.03$; model marginal $R^2=0.11$); there were no significant effects of code-switching experience. Exploring further, it again seemed that more balanced language exposure was associated with faster reading. This effect appeared uniform within unilingual sentences, but was greater for code-switched verbs than for code-switched nouns.

Cognitive Control Manipulation

We predicted that after incongruent Flanker trials—which experimentally increase cognitive control engagement relative to congruent trials—bilinguals would demonstrate smaller switch costs. A model was run to predict logged 3-word reading time with fixed effects of sentence type, prior Flanker congruency, block (first or second half of experiment), and default language, along with a centered length covariate. Block was included because a similar cognitive control manipulation had different effects in different experimental halves (Adler et al., 2020).

The model revealed similar effects of sentence and default language as models discussed above. There was a main effect of block ($\beta=-0.21$, $\eta_p^2=0.41$, $p<0.0001$; model marginal $R^2=0.14$); responses became faster in the second half of the experiment. Against our prediction, there was no effect of or interaction involving prior Flanker congruency ($\eta_p^2=0.003$, $p=0.52$): Prior cognitive control engagement did not seem to affect switch costs.

Three additional exploratory models with additional predictors in the model also found no effects of prior Flanker congruency, even when including code-switch type (determiner-noun vs. perfective vs. progressive), language experience (code-switching experience and language entropy), or the location of the first switched word in the sentence. In two more exploratory models, we re-ran the model with comprehension question reaction time or accuracy as the dependent variable to determine if cognitive control engagement had a later effect on offline comprehension; again, we found no effects of prior Flanker congruency.

As a manipulation check, we confirmed that Flanker congruency did affect responses to Flanker trials, observing the classic effect of slower response times ($\beta=0.188$, $\eta_p^2=0.90$, $p<0.01$) and lower accuracy ($\beta=-6.15$, $p<0.0001$) for incongruent trials than congruent ones. That is, the cognitive control manipulation worked but did not affect switch costs.

Discussion

Summary of Main Findings

In this study, we tested whether the statistical regularities of various types of code-switches that speakers produce regulate the costs of integrating a code-switch during real-time comprehension. Bilinguals experienced smaller switch costs for progressive verb-phrase switches than perfective verb-phrase switches; for auxiliary-location verb-phrase switches than participle-location verb-phrase switches; and for switches within noun-phrases as compared to verb-phrases. These findings align with the predictions of the PDC model: More frequent switch types in production elicited smaller switch costs in comprehension. This suggests that bilinguals' processing of code-switches is influenced by probabilistic constraints on where intrasentential switches are likely to occur, and provides insight into why the magnitude of switch costs may

vary in previous observations. Overall, this pattern links frequency in production to ease of comprehension and suggests a role for statistical learning mechanisms in bilingual language comprehension that modulate the magnitude of switch costs. Masculine noun switches, however, induced similar switch costs to feminine noun switches, which is ostensibly inconsistent with the predictions of the PDC model (but see further discussion below). Our findings support the general idea that the PDC model applies to the processing and comprehension of code-switched input. Although other situational factors are relevant, production patterns can explain significant variation in switch costs across multiple contexts.

Conflict in Comprehension of Code-switches

Our findings indicate that bilinguals are able to learn the distributions of code-switch types and process frequent switches more easily than infrequent ones. How might the statistically more common switches in production result in smaller switch costs during comprehension?

Recall that switch-cost magnitude may reflect the amount of conflict that bilinguals experience when processing the code-switch (Adler et al., 2020; Wu & Thierry, 2013). Under this explanation, more frequent switches may come to elicit less conflict given repeated exposure over time. Consequently, more frequent switches may require less time for conflict resolution, and result in smaller switch costs. This largely aligns with the results we found in which bilinguals read more frequent switch types faster.

If this explanation is correct and switch costs do reflect the time needed for cognitive control operations to resolve cross-linguistic conflict, then we would predict that increased engagement of cognitive control before encountering a code-switch would also result in smaller switch costs. This is because when cognitive control is experimentally upregulated, it remains

engaged during the processing of ensuing conflict on a subsequent trial, helping people meet task demands, including during language processing (e.g., Hsu & Novick, 2016; Hsu et al., 2021; Ovans et al., 2022; Thothathiri et al., 2018). However, we found that upregulating cognitive control with an incongruent Flanker trial, compared to a congruent one, before a code-switch did not impact our measure of switch costs. Given the null result, we are not licensed to draw any inferences, but we speculate on a few reasons why the Flanker manipulation failed to modulate sentence processing as it has in prior studies. One possibility is that, while our self-paced reading paradigm was sensitive enough to detect differences in switch costs, it may not have been sensitive enough to detect a small interaction between prior Flanker and current sentence trial types. Indeed, prior research observing such interactions has done so using dependent measures that have finer-grain temporal resolution, like changes in eye-movement patterns during spoken comprehension (Hsu & Novick, 2016; Hsu et al., 2021; Navarro-Torres et al., 2019; Thothathiri et al., 2018) and evoked-response potentials in the EEG record (e.g., the P600 effect; Ovans et al., 2022). Future research should address whether cognitive-control engagement impacts processing costs associated with comprehending a code-switch using methods that have more responsive timing characteristics.

In addition, we note that if more frequent types of switches elicit relatively little conflict, as our findings primarily suggest, then the *need* for cognitive control may be reduced in such situations. Thus, in general, variations in the state of cognitive control should have limited effect on the processing of code-switch types that recur with high statistical regularity in natural input. While an exploratory analysis that includes code-switch type did not find evidence for an effect of our cognitive control manipulation, future studies that explicitly manipulate frequency of code-switch structures in a similar design should further investigate this hypothesis.

Given these considerations, we continue to interpret our results as indicating that bilinguals are able to learn the statistical distributions of code-switch types and apply that learning to comprehension processes. In what follows, we consider why the statistical learning account failed to accurately predict some of our results, as well as review alternate explanations of our results and the limitations of those explanations.

Why didn't Code-switching Experience Modulate Switch Costs?

Although many of our results support the interpretation that the PDC model can explain switch cost variation, we did not find any effect of individuals' code-switching experience, as the model would predict. Under the PDC model, it is specifically those with exposure to various constructions (here, switches) that learn the statistical regularities of code-switches in the input, which affects processing. Against our prediction, we found no effect of code-switch experience—as calculated based on self-reported exposure to and production of code-switches—on switch-cost magnitude. We also found no reliable pattern for effects of language entropy, a measure of daily language exposure balance: More balanced language exposure seemed to afford participants a faster reading speed at times, but not in any pattern that clearly aligned with production frequency. It may be that our remote self-paced reading technique was not sensitive enough to pick up on any interactions between PDC effects and individual experience. It is also possible that our self-report code-switching questions did not measure code-switching experience with enough sensitivity. The field is moving towards well-validated measures of code-switching experience (e.g., Bilingual Code-switching Profile, Olson, 2022), which will provide a more sensitive measure. Similarly, our sample may have been too homogenous on the experience dimension, or perhaps only a small amount of code-switching exposure is needed to observe the

predicted frequency effects. Prior studies that have examined code-switching experience have focused on between-group comparisons where greater differences are observed in habitual code-switching practices (e.g., Beatty-Martínez & Dussias, 2017; Valdés Kroff et al., 2018). Given these possibilities, we do not interpret the lack of individual language experience effects as necessarily problematic for the PDC model. Future work should continue to test for the effect of individual experience on comprehension of code-switches and how it interacts with other predictors of switch-cost magnitude such as production frequency.

Relatedly, future work should test whether a person's level of experience specifically affects their processing of less regular code-switches, as expected under a constraint-based model of language comprehension (MacDonald & Christiansen, 2002). This is because the ease with which irregular constructions are interpreted (e.g., object relative clauses, or perhaps code-switches at idiosyncratic syntactic sites) relies heavily on how much exposure to that identical construction an individual receives (Wells et al., 2009; Juliano & Tanenhaus, 1994). Such a frequency-by-regularity interaction might be especially relevant to capturing effects of experience on switch costs during comprehension. In line with such predictions, one might expect that such frequency effects may result in differential priming (i.e., less frequent code-switch constructions should result in greater priming effects).

Why didn't Frequency Predict Noun-Phrase Switch Costs?

Most of our findings support the inference that the PDC model applies to the comprehension of code-switches; however, we found that more frequent masculine noun switches were *not* easier to process than less frequent feminine noun switches. One explanation for this null effect is that masculine noun switches *are* easy to comprehend due to their

frequency, but feminine noun switches evoke a similar processing “boost” that balances out the expected regularity effect. Feminine determiner-noun switches, unlike masculine ones, provide the comprehender with advanced information about the imminent noun. Despite their relatively low frequency, this informativeness might facilitate processing of feminine noun switches.

Because it is acceptable for a Spanish masculine determiner to occur before an English noun with either a masculine or feminine Spanish translation, masculine determiners are not informative about the approaching noun in the way that feminine determiners are: Feminine determiners *reliably* precede a feminine Spanish noun or an English noun that would be feminine in Spanish.

Eye-tracking research supports this view: Spanish monolinguals, but not Spanish-English bilinguals, use masculine determiners as a reliable predictive cue during comprehension, whereas all Spanish speakers use feminine determiners as a predictive cue (Valdés Kroff et al., 2017). Thus, while masculine code-switched noun phrases are a more frequent code-switch type than feminine code-switched noun phrases, they may not be read any faster because feminine determiners, though infrequent, evoke facilitatory predictive processes. This explanation is consistent with the main idea of the PDC model—that comprehenders learn distributional patterns, and this knowledge guides real-time processing. However, simply comparing more and less frequent types of switches may mask some of the subtlety of the learning process and the type of distributional information people track. Although we find this to be a reasonable description of what may be happening in the current study, a null result cannot be taken as evidence; future research should test how such learned patterns of predictability might offset other effects of frequency.

There are additional possible explanations for this null result. One reason for the lack of a grammatical gender effect could be that the self-paced reading paradigm is not sensitive enough to detect comprehension differences previously observed in the EEG record (Beatty-Martínez & Dussias, 2017; Beatty-Martínez & Dussias, 2019). Yet the presence of other frequency effects on comprehension makes this explanation unlikely. Additionally, although our participants indicated moderate levels of code-switching experience, research indicates that bilingual communities exhibit a range of different code-switching practices—with some using code-switched noun phrases more than others (Beatty-Martínez & Dussias, 2019). Without directly testing the participants' production tendencies or exposure, we cannot eliminate the possibility that their code-switching experience simply does not follow the pattern of using more frequent masculine determiners that we observed in our reference corpus (Beatty-Martínez & Dussias, 2017). However, this is unlikely to be a satisfactory explanation, as even non-habitual code-switchers show a preference for masculine determiner code-switches to some degree (Beatty-Martínez & Dussias, 2017).

Alternative Interpretations of Current Findings

Thus far, we have assumed that the observed differences in switch costs are caused by the variable of interest: production frequency. However, other interpretations of our results remain. One possibility is that our effects are due to linguistic complexity. For instance, switches within verb phrases may elicit larger switch costs than switches within noun phrases not because they are less frequent, but because they are more morphologically complex (Myers-Scotton, 1993; Myers-Scotton & Jake, 1995, 2001, 2009). Indeed, morphological complexity is at the heart of Myers-Scotton's Matrix Language Framework, which takes the morpheme as the most important

unit for where code-switches can take place (Myers-Scotton & Jake, 2009). Nouns are generally likelier junctures for code-switches to take place because they involve switching at content morphemes. Verbs often involve greater inflectional morphology, thus making verb sites less likely candidates for code-switching or candidates for creative bilingual constructions, such as verb switching where the root content morpheme remains uninflected and the inflectional morphology is carried by a light verb (e.g., *Los residentes hacen cook*; English gloss: The residents do[3rd person plural morpheme] cook; English translation: “The residents cook;” Balam et al., 2020; Chan, 2009). However, linguistic complexity alone cannot explain why progressive tense switches and switches at the participle location result in smaller switch costs than perfect tense switches and switches at the auxiliary location. Progressive and perfective tense verbs are similarly complex (Giancaspro, 2015; Guzzardo Tamargo et al., 2016); thus, we assert that distributional patterns in production frequency are a more consistent predictor of switch-cost magnitude.

Another possibility is that predictability of code-switches within the context of our experiment better explains our results than lifelong exposure to and learning of regular and irregular types of switches. For instance, if our switches within noun phrases were located in more consistent and predictable sites in our stimuli than switches within verb phrases, this could have resulted in smaller switch costs. However, this was not the case. Noun-phrase switches could occur at any noun in critical sentences, resulting in a fairly unpredictable switch location. Often, the switch occurred at the first noun after the first verb of the sentence such as in Example (2), but this was variable as multiple critical noun sentences had switches at other points in the sentence, such as in Example (3). However, verb-phrase switches followed a much more predictable pattern, with switches always occurring in the second verb phrase of somewhat

formulaic sentences as shown in (4) and (5) (following the controlled stimuli in Guzzardo Tamargo et al., 2016). If our results were driven by predictability rather than production frequency, we would expect more predictable sentences such as the verb-site switches to result in smaller switch costs. Instead, our results show that more frequent noun switches are easier to process than less frequent switches within verb phrases despite the lower predictability of noun switches in our experiment.

(2) La familia buscó el neighborhood with the best neighbors. [*The family searched for the neighborhood with the best neighbors.*] (adapted from Johns et al., 2019)

(3) Asombrosamente, el detective encontró el violín que perdió en el south of Italy. [*Surprisingly, the detective found the violin that he lost in the south of Italy.*] (adapted from Adler et al., 2020)

(4) El dueño dijo que los arquitectos have signed the documents for the construction. [*The owner said that the architects have signed the documents for the construction.*] (adapted from Guzzardo Tamargo et al., 2016)

(5) El reportero confirmó que los senadores están requesting the funds for the project. [*The reporter confirmed that the senators are requesting the funds for the project.*] (adapted from Guzzardo Tamargo et al., 2016)

It is also worth noting that participants in different lists may have adopted different strategies based on the default language they were assigned. Some participants saw all unilingual sentences and questions in English, while others saw them in Spanish. However, code-switched sentences always started in Spanish and switched to English. We made this methodological

decision based on the sociolinguistic observation that code-switches are likelier to occur from Spanish to English for U.S. Spanish-English bilingual populations (Beatty-Martínez & Dussias, 2017; Blokzijl et al., 2017; Valdés Kroff et al., 2018), which follows a more general trend for code-switches to go from a minority language into a majority language in minority-majority language settings (Parafita Couto & Gullberg, 2019). Therefore, participants in an English default language list would know with certainty that a switch was coming if the sentence started in Spanish, potentially allowing them to be more prepared for the switch, although they would not necessarily know where exactly the switch would occur, especially for the noun switches. On the other hand, participants in the Spanish default language list may have increased their global suppression of English (most participants' dominant language) given that the majority of input was in Spanish. This could have made switches even more difficult for participants in the Spanish default lists. If these strategies were adopted, we might expect those in the English default lists to experience smaller switch costs as they more easily predict switches and globally activate English. Against this alternative prediction, as shown in Figures 4 and 7, those in the English default language actually experienced *larger* switch costs.

However, the larger switch costs could be due to another factor obscuring possible benefits to the English default list participants. When calculating switch costs for English default list participants alone, we compare reading times of switched English words with unswitched English words. Here, we see clear switch costs. When calculating switch costs for Spanish default list participants alone, we compare reading times of switched English words with unswitched Spanish words. Here, we see no switch costs. Our participants were largely English-dominant and read much faster in English than in Spanish, as can be seen by the differences in unilingual reading times in Figure 4. Thus, the apparent lack of difference between code-

switched and unilingual reading in the Spanish default list may actually reflect a switch cost: Participants were overall faster when reading in English, but they read the code-switched English region as slowly as an unswitched Spanish region. Given this reading time difference, direct comparisons of switch-cost magnitudes between these groups may not be easily interpretable. Therefore, we re-ran our models separately for each default language group to determine if different experimental strategies could be affecting our results. The main patterns were largely unchanged when analyzing the data in this way, indicating that the different default languages did not seem to result in meaningfully different strategies adopted in the experimental setting.

Closing Remarks

The current study provides evidence that the PDC model is a useful framework for explaining variation in switch costs during comprehension for a wide range of code-switch types. Overall, consistent with prior findings, switches that are more frequent in production tended to evoke less processing difficulty. However, we expand on past work by delineating how code-switching patterns in production influence the costs of comprehending them, linking bilingual sentence processing to a broader set of effects that motivate the PDC model. Although there remain many questions about the type of conflict involved, the role of cognitive control, and the effects of individual experience on the comprehension of code-switches, this study is a step towards understanding patterns in code-switching behavior.

Additionally, although it was not our primary focus, our study provides insights into the feasibility and suitability of remote reading experiments on code-switching. Prior work has raised the issue of ecological validity of different experimental methodologies (Beatty-Martínez et al., 2018; Valdés Kroff et al., 2018) when testing the online processing of code-switches. This

issue is particularly salient for Spanish-English code-switching due to its stigmatization (Zentella, 1997) and that it is primarily a spoken language phenomenon. Our results corroborate online sensitivities to distinct code-switch types using a remote self-paced reading paradigm, despite the ability for participants to be distracted and that they participated from disparate communities across the U.S. Our findings thus suggest that code-switching research can be expanded to remote studies, which will, we hope, lead to an increase in experimental studies focused on bilingual language practices with more diverse samples.

Characterizing the conditions under which bilinguals experience switch costs can spell out the processing demands involved in situations where multiple languages are in use, and the contexts in which code-switching might be beneficial to integrate into educational environments. In the U.S., a common policy in educational practice is to separate languages (see Lin, 2013 and Macaro, 2009 for discussion), citing concerns about student confusion that are not empirically supported (Antón et al., 2015; 2016; see also Byers-Heinlein & Lew-Williams, 2013; Mallikarjun et al., 2017). Although code-switching may (or may not) introduce slow-downs in comprehension, code-switching may also promote learning and student-teacher trust (Canagarajah, 2006; Cook, 2001; Lin, 2013). Given that code-switches offer potential educational benefits to learning and student-teacher relationships, we need to better understand *when* to incorporate code-switches into the classroom—guidance that some teachers have expressed a desire for (Hopewell et al., 2020). This study documents when code-switches are least costly and the degree to which code-switch processing difficulty is determined by relatively stable frequency distributions versus contextual factors. By clarifying the factors that modulate the ease with which bilinguals process different types of switches, we can begin to form a foundational understanding of how and when code-switches affect comprehension difficulty, and

map out the types of switches that may be most useful in education and the contexts in which they may best be employed.

Data availability: The data that support the findings of this study are openly available on OSF at <https://osf.io/5yzna/>. Note that data is only available for participants who consented to data sharing. The materials used to conduct the study are also available at the same link.

Competing interests: The author(s) declare none.

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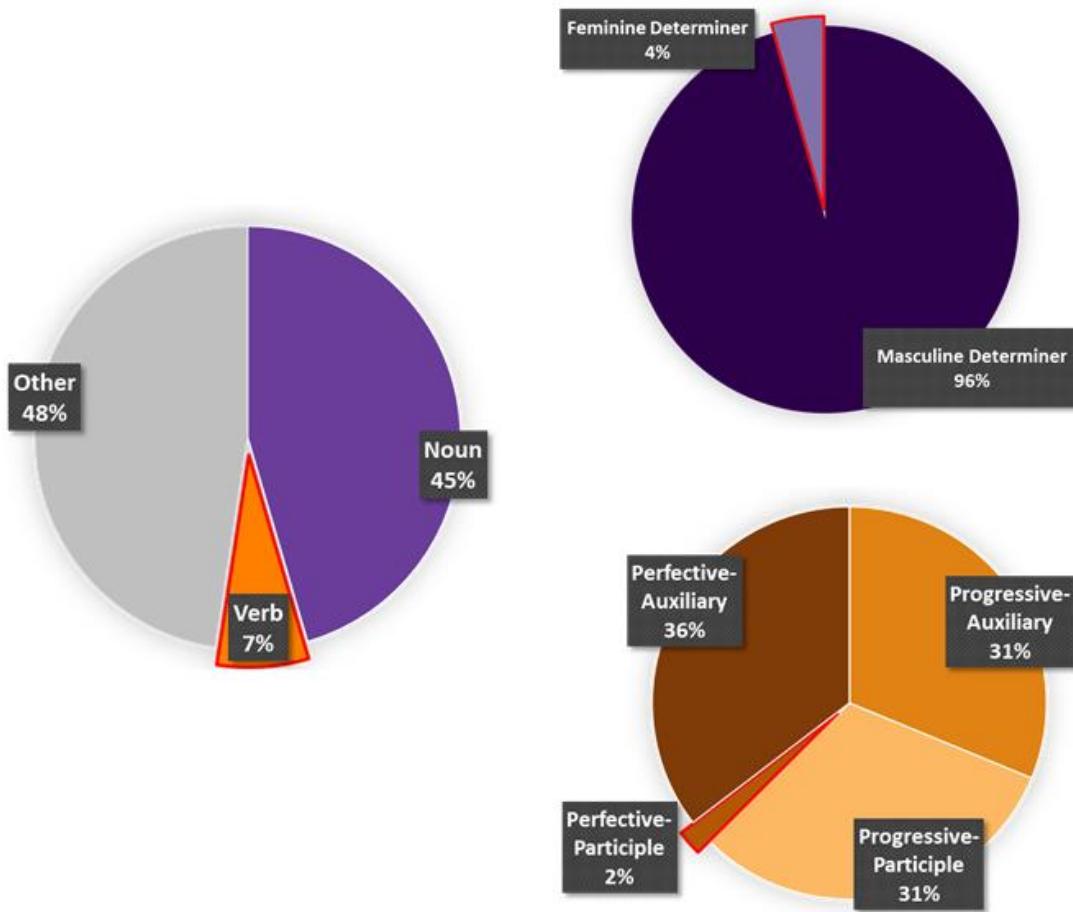
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Figure 1. *Distributions of Code-switch Types in Bilingual Language Production.*



Note. The left pie chart represents all intrasentential code-switches from a corpus of speech from Puerto Rican bilinguals in New York City; the Other category accounts for all code-switches not in noun or verb phrases, such as switches at prepositions or adverbs (Poplack, 1980, Table 2). The upper right pie chart in purple represents all Spanish determiner to English noun code-switches from a corpus of speech from code-switching bilinguals in the U.S. (Beatty-Martínez & Dussias, 2017, Table 9). The lower right pie chart in orange represents all Spanish to English code-switches within perfective or progressive verb phrases from an analysis of an oral corpus from bilinguals in Miami and a written corpus from a Gibraltar newspaper (Guzzardo Tamargo et al., 2016, Table 1). Red-outlined wedges indicate the least frequent type of switch within each pie chart.

Table 1. *Participants' Language History (n=101).*

<u>Characteristic</u>	<u>Mean</u>
Age (range in parentheses)	22.8 (18-55)
AoA English (range in parentheses)	3.10 (0-17)
AoA Spanish (range in parentheses)	2.30 (0-19)
English grammar score (out of 20)	16.00 (2.76)
Spanish grammar score (out of 20)	13.72 (3.53)
Self-Rated English Ability (max = 10)	9.59 (0.69)
Self-Rated Spanish Ability (max = 10)	8.45 (1.31)
Code-switching Experience (max = 5)	2.97 (0.83)
<u>Language Exposure Entropy (max = 1.58)</u>	<u>0.89 (0.25)</u>

Note. Standard deviation in parentheses unless otherwise noted.

AoA = Age of Acquisition

Table 2. *Types of Code-switches in Critical Sentences.*

96 Critical Sentences							
48 Noun Phrase				48 Verb Phrase			
24 Masculine		24 Feminine		24 Perfect Tense		24 Progressive Tense	
12 at participle	12 at auxiliary	12 at participle	12 at auxiliary	12 at participle	12 at auxiliary	12 at participle	12 at auxiliary
Ex.: <i>el lake</i>	<i>la milk</i>	<i>los</i>	<i>los</i>	<i>los</i>	<i>los</i>	<i>los</i>	<i>los</i>
		<i>modelos</i>	<i>editores</i>	<i>banqueros</i>	<i>estudiante</i>		
		<i>han</i>	<i>have</i>	<i>están</i>	<i>s are</i>		
		<i>signed</i>	<i>approved</i>	<i>preparing</i>	<i>checking</i>		

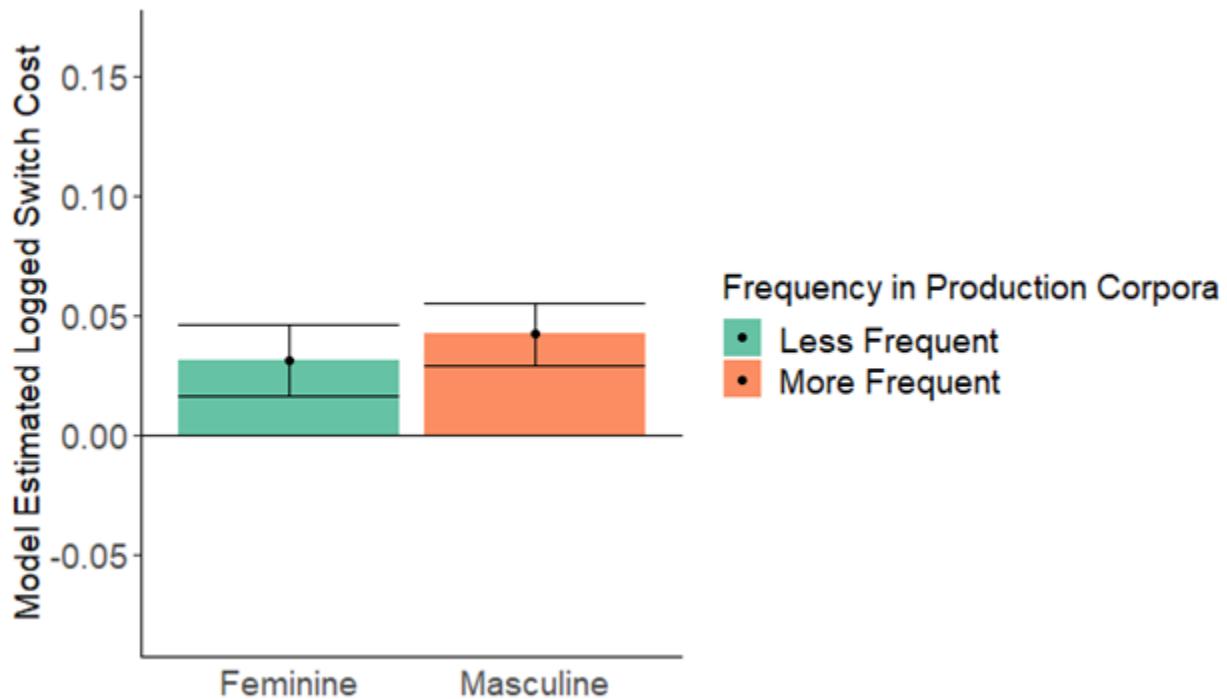
Figure 2. *Regions of Analysis*.

La electricista tiene la box with her tools.

El reportero dijo que las modelos han signed a contract with the agency.

Note. Each underlined region was analyzed as pre-registered. Here, we report only analyses on the red underlined region that represents the switch (or single-language equivalent) plus the two subsequent words. For noun switches, the switch was considered the noun. For switches within verb phrases, the switch was considered the auxiliary + participle.

Figure 3. *Noun Switches: Comprehension Switch Costs by Production Frequency.*



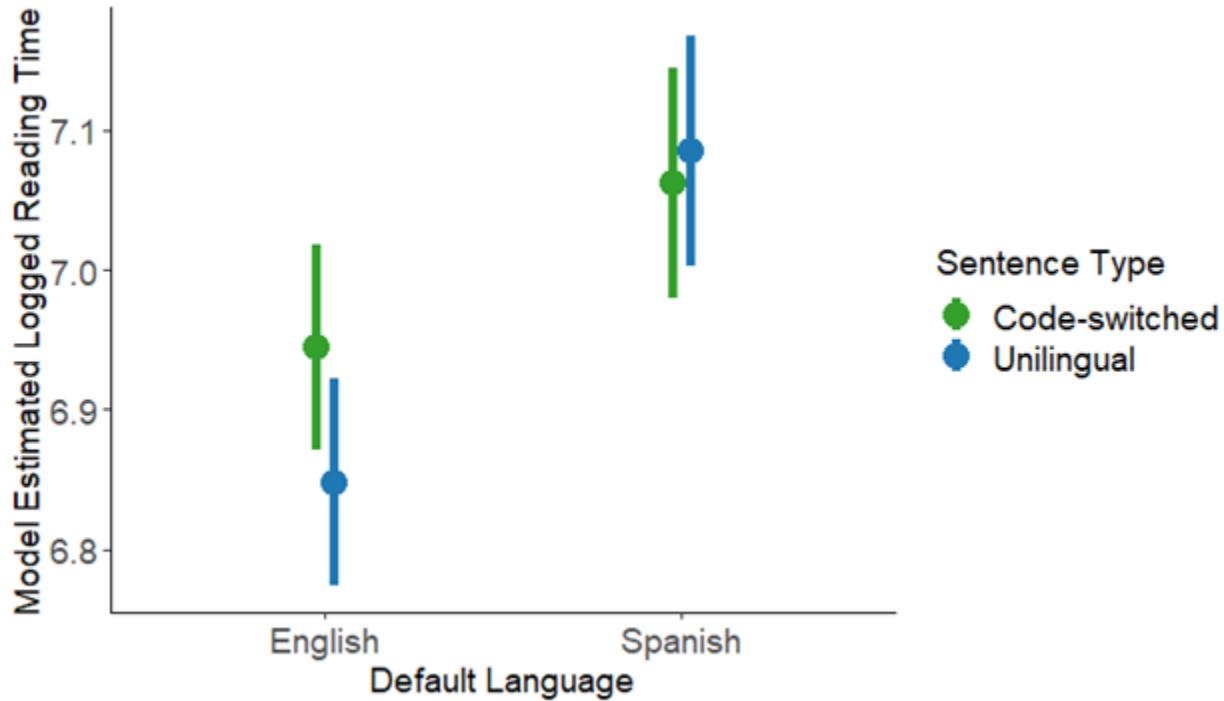
Note. The y-axis represents the difference between the model's predicted logged reading time (in ms) for the region of interest in code-switched sentences vs. single-language equivalents. Bars represent standard error generated by the emmeans R package.

Table 3. *Raw Switch Costs for 3-word Noun Region.***Determiner Mean Switch Cost**

Feminine 44ms

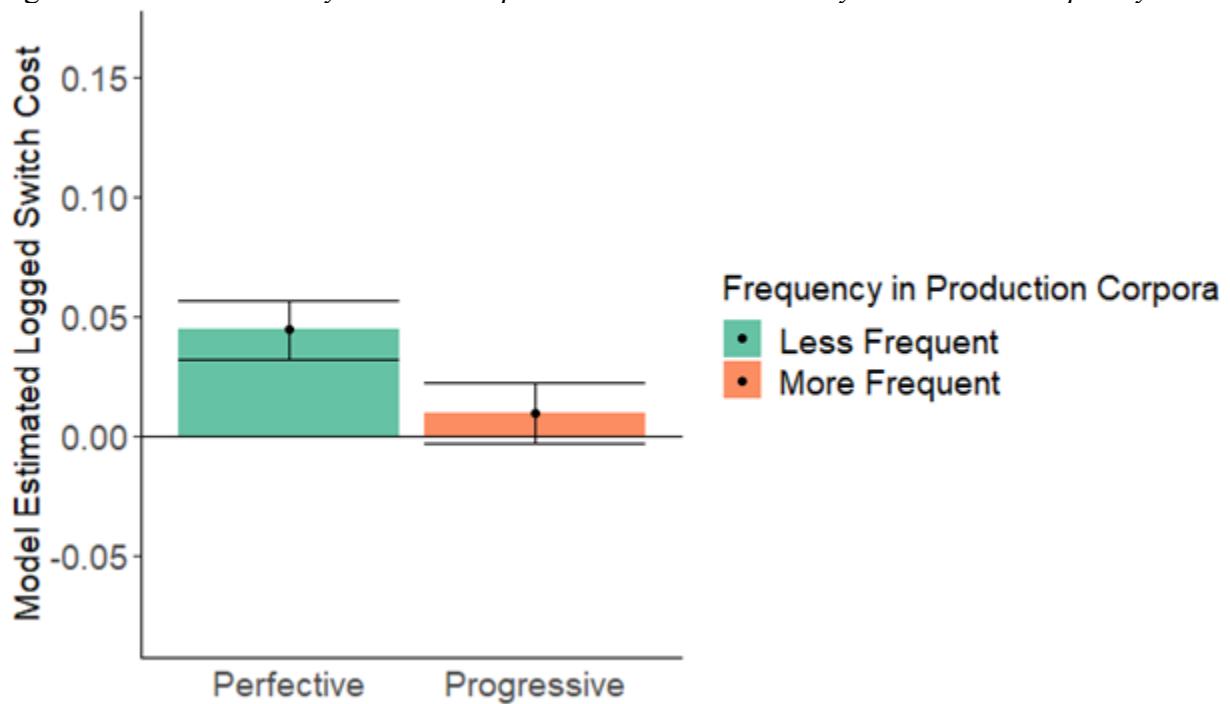
Masculine 57ms

Figure 4. *Noun Switches: Reading Differences by Default Language.*



Note. The y-axis represents the model's predicted logged reading time (in ms) for the region of interest. Bars represent 95% confidence intervals generated by the emmeans R package using the emmip function. Since all code-switches were from Spanish to English, here we see reading times for English words in both code-switched conditions and the English unilingual condition; reading times for the Spanish unilingual conditions are for Spanish words.

Figure 5. *Verb Switches by Tense: Comprehension Switch Costs by Production Frequency.*

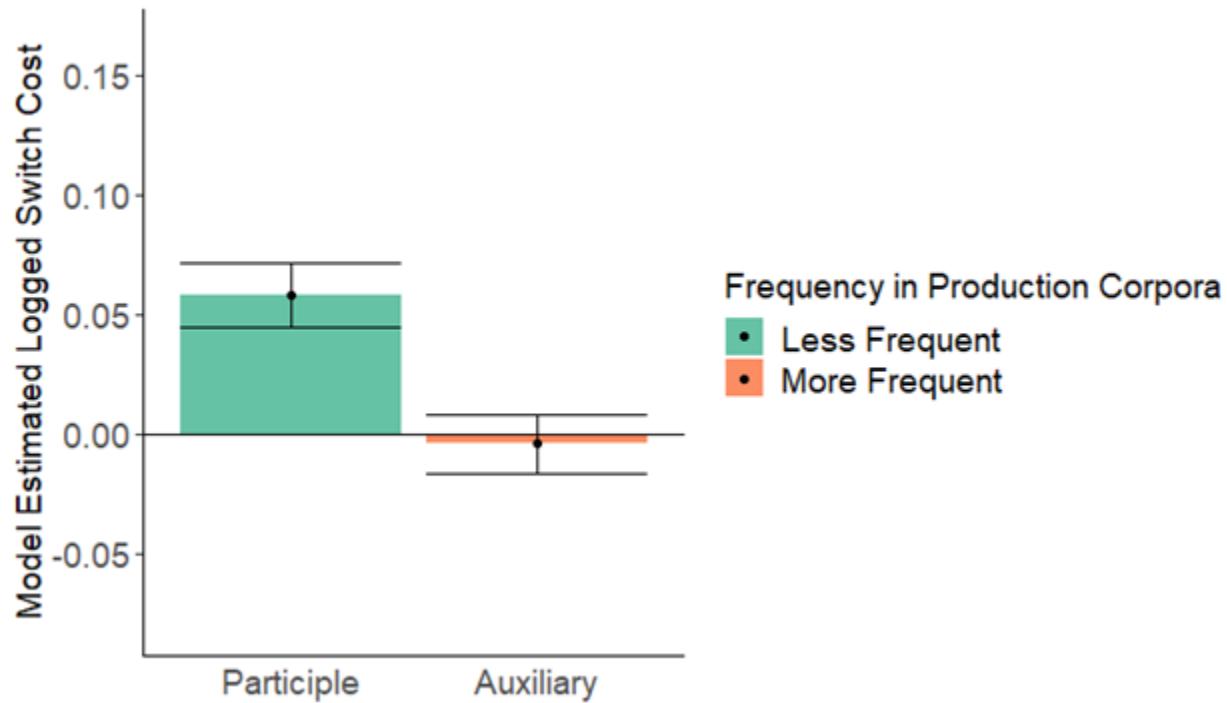


Note. The y-axis represents the difference between the model's predicted logged reading time (in ms) for the region of interest in code-switched sentences vs. single-language equivalents. Bars represent standard error generated by the emmeans R package.

Table 4. *Raw Switch Costs for 4-word Verb Region: Verb Tense.*

<u>Verb Tense</u>	<u>Mean Switch Cost</u>
Perfective	64ms
Progressive	21ms

Figure 6. *Verb Switches by Switch Location: Comprehension Switch Costs by Production Frequency.*



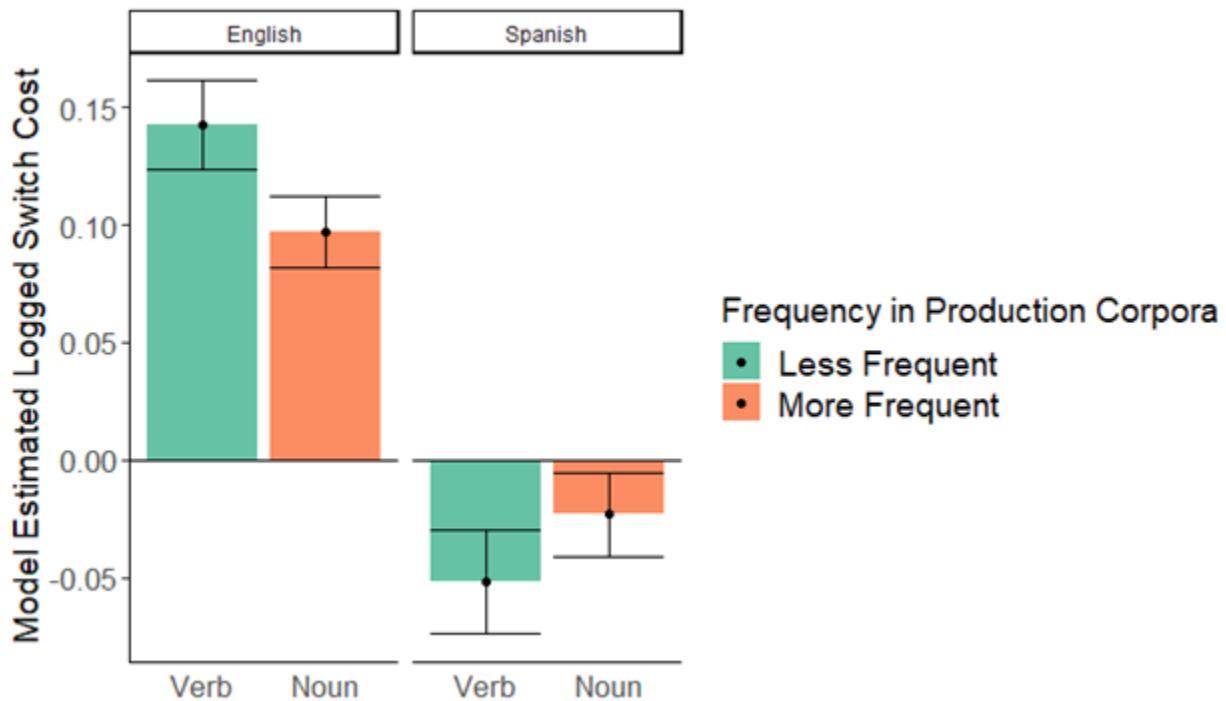
Note. The y-axis represents the difference between the model's predicted logged reading time (in ms) for the region of interest in code-switched sentences vs. single-language equivalents. Bars represent standard error generated by the emmeans R package.

Table 5. *Raw Switch Costs for 4-word Verb Region: Switch Location.***Switch Location** **Mean Switch Cost**

Participle 98ms

Auxiliary -15ms

Figure 7. *Noun vs. Verb Switches: Comprehension Switch Costs by Production Frequency.*



Note. The y-axis represents the difference between the model's predicted logged reading time (in ms) for the region of interest in code-switched sentences vs. single-language equivalents. Bars represent standard error generated by the emmeans R package. Plot is split by the comparison language: whether the switch cost is calculated by comparing code-switched region reading to reading of fully English equivalent regions or of fully Spanish equivalent regions.

Table 6. *Raw Switch Costs for 3-word Region.*

<u>Switch Type</u>	<u>Default Language</u>	<u>Mean Switch Cost</u>
Verb	English	143ms
Noun	English	102ms
Verb	Spanish	-89ms
Noun	Spanish	-19ms