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Cognitive and Neural Control in Bilingual Language Processing

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy

in

Clinical Psychology

by

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Committee in charge.

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The Dissertation of Alena Stasenko is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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San Diego State University

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DEDICATION

In loving memory of my grandmother, Roza, who always believed in me and supported my research and career ambitions despite being almost 3,000 miles away. Thank you for being my number one fan.

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PUBLICATIONS

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Stasenko, A., Jacobs, D., Salmon, D.P, & Gollan, T.H. (2019). The Multilingual Naming Test (MINT) as a measure of picture naming ability in Alzheimer's disease. *Journal of the International Neuropsychological Society, 25,* 821-833.

Stasenko, A., & Gollan, T.H. (2019). Tip-of-the-tongue after any language. Reintroducing the notion of blocked retrieval. *Cognition*, *193*, [epub ahead of print].

Smirnov, D., **Stasenko, A**., Salmon, D.P., Galasko, D., Brewer, J.B., Gollan, T.H. (2019). Distinct structural correlates of the dominant and non-dominant languages in bilinguals with Alzheimer's disease. *Neuropsychologia*, *132,* [epub ahead of print].

Gollan, T.H., Li, C., **Stasenko, A**., & Salmon, D. (2019). Intact reversed language-dominance but exaggerated cognate effects in reading-aloud of language switches in bilingual Alzheimer's disease. *Neuropsychology, 34,* 88-106.

Segal, D., **Stasenko, A**., & Gollan. T.H (2018). More evidence that a switch is not (always) a switch. Binning bilinguals reveals dissociations between task and language switching. *Journal of Experimental Psychology. General*, *148*, 501-519.

Stasenko, A., Matt, G., & Gollan, T. H. (2017). A relative bilingual advantage in switching with preparation. Nuanced explorations of the proposed association between bilingualism and task switching. *Journal of Experimental Psychology. General, 146,* 1527-1550.

Gollan, T.H., **Stasenko, A**., Li, C., Salmon, D.P. (2017). Bilingual language intrusions and other speech errors in Alzheimer's disease. *Brain and Cognition, 118*, 27-44.

Stasenko, A., Bonn, C., Teghipco, A., Garcea, F.E., Sweet, C., Dombovy, M., McDonough, J., Mahon, B.Z. (2015). A causal test of the motor theory of speech perception. A case of impaired speech production and spared speech perception. *Cognitive Neuropsychology, 32,* 38-57.

Stasenko, A., Garcea, F.E., Dombovy, M., & Mahon, B.Z. (2014). When concepts lose their color. A case of object color knowledge impairment. *Cortex, 58,* 217-238.

Stasenko, A., Garcea, F.E., & Mahon, B.Z. (2013). What happens to the motor theory of perception when the motor system is damaged? *Language and Cognition, 5,* 225-238.

ABSTRACT OF THE DISSERTATION

Cognitive and Neural Control in Bilingual Language Processing

by

Alena Stasenko

Doctor of Philosophy in Clinical Psychology

University of California San Diego, 2020
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Professor Tamar H. Gollan, Chair
Professor Christina E. Wierenga, Co-Chair

Bilingual individuals seem to easily speak in just one language, and switch back and forth between languages, suggesting they have powerful mechanisms for controlling activation of their two languages. A prominent theory suggests that cognitive control, and specifically inhibition of the non-target language, enables successful switching. We used behavioral and neuroimaging methods to study Spanish-English bilinguals to determine. 1) if college-aged bilinguals show an advantage in general task-switching ability relative to monolinguals given bilinguals' extensive practice with language switching; 2) if cognitive control regions are recruited in bilingual language *comprehension*, and 3) if an aging deficit in inhibitory control affects older bilinguals' (age 65+) ability to switch languages. In Study 1 (*n* = 80 per group; Stasenko et al., 2017) bilinguals exhibited more efficient task-switching, but only when participants had longer preparation time, and the advantage dissipated quickly. These findings suggest

that although bilingualism improves the efficiency of task switching, this advantage might be more related to preparing to switch than to switching per se. In Study 2 ($n = 24$; Stasenko et al., 2020), bilinguals recruited fronto-parietal brain regions (i.e., right frontal inferior gyrus, bilateral middle frontal gyrus, and left supramarginal gyrus) when switching relative to not switching languages even in silent reading of mixed language paragraphs (without producing any switches in their speech). These results suggest that although reading comprehension seems to be passive, it recruits brain regions known to support cognitive control, possibly reflecting a modality-general switch mechanism. Study 3 (ns = 48 and 25; Stasenko et al., submitted) revealed a reversal of language dominance in mixed-language testing blocks, and a transfer of inhibition from a repeated set of items to a new set of items (that was introduced halfway through the task). Both effects were found only in younger but not in older bilinguals. Overall, these findings support the role of domain-general cognitive control and inhibition as an important mechanism in bilingual language control that spans across production and comprehension and exhibits decline in healthy aging.

INTRODUCTION TO THE DISSERTATION

C*ognitive control* is an important human ability that enables flexibly switching between tasks, maintenance of multiple simultaneous concepts, and inhibition of irrelevant responses in the service of goal-directed behavior. Bilingual individuals constantly exercise a related form of control—language control—that is, they seem to effortlessly manage dual-language activation to enable switching between languages when needed, while also avoiding switching by mistake. It is presumed that a bilingual's two languages are always active to some extent, which suggests a heavier computational load for the brain than monolingualism. Accumulating evidence has shown that bilingualism changes the structure and function of the brain in a similar way to years of education, cognitive and social engagement, and expertise in different skills (Kramer et al., 2004). Examining the intersection between language control and cognitive control, and how these processes change in aging, may have important implications for language learning, experience-related neuroplasticity, and diagnosis and treatment of bilingual individuals. This is a topic of great relevance as bilingualism is prominent in most parts of the world, but even in the U.S.A monolingualism is becoming less common such that bilinguals now represent approximately 20% of the U.S. population, a number that is rapidly increasing.

In the spotlight of current research on bilingualism is the extent to which mechanisms responsible for selecting which language to speak overlap with general cognitive control processes that allow humans to flexibly switch between tasks (Abutalebi et al., 2012; for reviews see Abutalebi & Green, 2008; Declerck & Philipp, 2015). A cognitive control advantage for bilinguals might be expected given that bilinguals frequently switch languages in their daily life, which involves deciding which language to speak with whom, inhibiting the non-target language, reactivating it when necessary, and monitoring this process constantly. Consistent with the "shared linguistic and nonlinguistic control mechanisms" hypothesis (e.g., Abutalebi & Green, 2008) are behavioral studies in which bilinguals outperformed monolinguals on aspects of executive function including nonlinguistic task-switching, working memory and inhibition (Dong & Li, 2015 for review). Additional support for the shared mechanisms hypothesis comes from findings that bilingualism may serve as a form of "cognitive reserve"—a protective factor against age-related cognitive decline such as Alzheimer's disease (for review see Bialystok et al., 2017; Guzmán-Vélez & Tranel, 2015). Finally, neuroimaging studies also support the assumption of overlap in neural mechanisms involved in language control and executive control (Abutalebi et al., 2012; Abutalebi & Green, 2007, 2008; Blanco-Elorrieta & Pylkkänen, 2016; De Baene, Duyck, Brass, & Carreiras, 2015; Garbin et al., 2010; Ma et al., 2014; Weissberger et al., 2015). That is, bilinguals activated regions of the brain hypothesized to support language control during nonlinguistic task switching. However, the shared mechanism hypothesis has been challenged (e.g., Paap & Sawi, 2014; Paap et al., 2017) while others have concluded a small effect size (e.g., $g = .08$; Lehtonen et al., 2018; de Bruin, Treccani, & Della Sala, 2015). Therefore, additional research is needed to help define the extent that bilingualism exhibits a cognitive advantage. Importantly, executive function is a broad umbrella term for multiple specific processes and is not a unitary construct (e.g., Miyake & Friedman, 2012). Thus, the field of bilingualism is (and the current studies are) moving toward delineating what specific aspects of bilingual language control overlap with domain-general cognitive control.

To that end, in this staple dissertation we examined the intersection between language and executive control in more detail by determining 1) whether younger (i.e., college-aged) bilinguals will show an advantage in general task-switching ability relative to monolinguals, 2) if cognitive control regions are recruited in bilingual language *comprehension*, and 3) if an aging decline in inhibition will affect older bilinguals' language switching ability.

The first gap in the literature is whether there is a bilingual advantage in task-switching—which at face value is seemingly the most obvious component of executive function that we would expect to be enhanced in bilinguals, given their extensive practice with language switching. However, current evidence on whether a task-switching advantage exists is mixed, in particular using the color-shape switching task. Also, it is unclear what *aspect* of switching (i.e., proactive versus reactive as measured by different types of processing costs) might bilinguals be better at and if factors like preparation time and number of trials affect the integrity of the supposed advantage. It is also not fully clear if processing costs (e.g., switch and mix costs) represent general switching ability. A study by Yehene and Meiran (2007) found that switch costs measured with a longer preparation time (i.e., cue-target interval or CTI) may better tap general switching abilities. Thus, we hypothesized that if switch costs observed at long CTI offer a better reflection of general switching ability than at short CTI, and if bilingual language switching shares processes with switching in general, then differences between bilinguals and monolinguals should also be more robust at a longer CTI.

A second surprising gap in research on bilingual language switching is that the vast majority of studies focused on switches in speech production—even though language switches must of course be both produced and comprehended. Thus, it is not known if the same cognitive control processes that support switching in production also play a role in *comprehension*, which arguably is more passive than production and may require less cognitive control. Only one neuroimaging study directly compared language switches in both production and comprehension, and to a nonlinguistic switching task, and found that switches in speech activated the dorsolateral prefrontal cortex, a region that was also active in nonlinguistic switching, whereas switches in comprehension instead activated the left anterior cingulate cortex, a region that was not associated with nonlinguistic switching in this study (Blanco-Elorrieta & Pylkkänen, 2016). Given few and mixed findings, it remains an open question if bilinguals might rely on cognitive control when they comprehend mixed-language speech.

Third, if bilinguals rely on cognitive control (i.e., a domain-general mechanism similar to that used by monolinguals) to achieve language control, and inhibitory control declines in aging (Zacks & Hasher, 1994) due to decreased efficiency and shrinkage of the frontal lobes (Raz et al., 2005; Tamnes et al., 2013), then older bilinguals should have more difficulty with language switching than younger bilinguals. In line with this prediction are reports of aging-related increases in processing costs in bilingual language switching tasks (de Bruin, Samuel, & Duñabeitia, 2020; Hernandez & Kohnert, 2015; Weissberger et al., 2012; but see Calabria et al., 2015). In addition to processing costs, another measure of bilingual language control comes from language *dominance reversal*, a presumed signature of global inhibition of the dominant language where bilinguals respond slower in the language that is otherwise usually more dominant or proficient. Two aging studies (Gollan & Ferreira; 2009; Gollan & Goldrick,

2016) found that older bilinguals, and even bilinguals with Alzheimer's disease (Gollan, Stasenko, Li, & Salmon, 2017; Gollan, Li, Stasenko, Salmon, 2019) showed reversed language dominance effects, implying intact ability to inhibit the dominant language similar to younger bilinguals. However, these involved voluntary (not required switches) or switches that were supported by production of connected speech. Thus, at present it is not fully clear the integrity of bilingual language control in aging, and whether older bilinguals will demonstrate reduced reversed language dominance.

Three studies address unanswered questions about language control in young and older Spanish-English bilinguals using behavioral and neuroimaging paradigms. Under the assumption of shared control mechanisms between linguistic and nonlinguistic cognitive control, in Study 1, we examined if switching ability in a nonlinguistic color-shape task is more efficient in bilinguals compared to monolinguals by manipulating the preparation interval. In Study 2, we used functional MRI with a paragraph reading task to examine the role of cognitive control in bilingual comprehension during switching. We predicted that silent reading will elicit activation in regions associated with domain-general cognitive control and will consist of regions commonly implicated as part of a 'language control network' (e.g., Abutalebi & Green, 2008; Luk et al., 2011 for meta-analysis). Study 3 investigated the possible role of inhibitory control in bilingual language production by using a cued picture naming test identified for its robust measurement of inhibitory control and which has previously shown strong evidence of language inhibition (Kleinman & Gollan, 2018). Specifically, we examined how reversed language dominance effects change over time and whether healthy older bilinguals will exhibit dominance reversal or if they will be unable to inhibit the dominant language.

Together, these chapters represent a detailed examination of the intersection between bilingual language processing, non-linguistic cognitive control, and aging. Results from these studies will constrain and further develop theoretical models of both bilingual language processing and more broadly cognitive control across the lifespan. By combining novel experimental paradigms that are more naturalistic (e.g., reading of full paragraphs) with classic paradigms (e.g., cued language switching) and with the added method of functional MRI, we will have a more complete understanding of the processing dynamics involved in bilingual language control and, importantly, how it interacts with nonlinguistic executive control abilities.

Chapter 1. Study 1

A Relative Bilingual Advantage in Switching with Preparation. Nuanced Explorations of the Proposed Association Between Bilingualism and Task Switching

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Abstract

Bilingual language switching may increase general switching efficiency, but the evidence on this question is mixed. We hypothesized that group differences in switching might be stronger at a long cue-target interval (CTI), which may better tap general switching abilities (Yehene & Meiran, 2007). Eighty Spanish-English bilinguals and 80 monolinguals completed a color-shape switching task, and an analogous language-switching task, varying CTI (short versus long) in both tasks. With longer preparation time (long CTI), bilinguals exhibited significantly smaller task-switching costs than monolinguals, but only in the first half of trials. Group differences diminished with practice, though practice benefitted RTs on short CTI trials more than long, and bilinguals committed fewer errors with practice especially at short CTI. Groups did not differ in mixing costs; however, across CTIs and tasks, bilinguals and monolinguals alike, exhibited robust correlations between mixing costs, but not between switching costs. These results confirm an association between bilingualism and switching efficiency that may be magnified with manipulations that target general switching ability (or could reflect better ability to take advantage of preparation time). However, practice effects observed within experimental paradigms, and between task correlations in costs, may reflect cognitive mechanisms specific to laboratory tasks much more than associations with general switching ability and executive control mechanisms– for which more reliable and valid measures can hopefully be developed in future work.

Keywords. bilingualism, task-switching, bilingual advantage, executive control, color-shape task

A Relative Bilingual Advantage in Switching with Preparation. Nuanced Explorations of the Proposed Association Between Bilingualism and Task Switching

Daily life requires constant flexibility and switching between tasks. Individuals seem to vary in the relative efficiency of their switching abilities, which can have significant consequences for managing and maintaining goal directed behavior, and ultimately professional and personal achievements. A high priority is to identify ways to maximize switching efficiency in any way possible. Implicit in this pursuit might be the assumption that some individuals are better switchers than others. What would characterize performance of an elite switcher? Undoubtedly, an elite switcher would be expected to respond quickly and accurately in a task that measures both switching and non-switching responses, but especially, or perhaps exclusively, on switch trials. We might also expect this switching advantage to be most apparent when individuals are given little time to prepare for upcoming switches. However, this expectation assumes that an integral part of switching ability includes an early stage—prior to execution of the switch itself— in which identification that a switch is needed takes place. Indeed, longer preparation time is known to reduce switching costs in both nonlinguistic (e.g., Monsell, 2003) and linguistic (e.g., Fink & Goldrick, 2015), switching paradigms—but little is known about how switching ability generally relates to preparation time. Finally, an elite switcher advantage might be expected to shrink with practice if elite switchers are more efficient, not because of naturally present switching ability, but because they have had (for one reason or another) more practice with switching than relatively less efficient switchers.

Bilingualism is one reason that might lead some people to switch more often than others. Bilinguals juggle both of their languages on a daily basis, and seem to do so without effort even when switching languages in mid-sentence during conversation with other bilinguals. This juggling process requires managing activation of both languages, possibly relying on the same inhibitory control mechanism thought to facilitate task-switching (Green, 1998; Meuter & Allport, 1999; Myers-Scotton, 2006). In the spotlight of current research is the extent to which mechanisms responsible for selecting which language to speak overlap with cognitive control processes that allow individuals to flexibly switch between non-linguistic tasks (Abutalebi et al., 2012; for reviews see Abutalebi & Green, 2008 Declerck &

Philipp, 2015). A main point of focus in this study is whether bilinguals appear to function like elite switchers in a non-linguistic switching task.

A switching advantage for bilinguals would be expected given that bilinguals frequently switch languages, and given a finding in experimental studies of language switching of many striking parallels between results found in linguistic and non-linguistic switching paradigms (e.g., when switching between judging objects by their color versus their shape). In both paradigms, *switching costs* are observed. That is, responses are slower on switch trials (in which the task changes relative to the previous trial), relative to non-switch or *stay* trials (in which the task stays the same as on the previous trial). Also found in both paradigms, are *mixing costs,* which reflect the fact that responses are slower on non-switch trials in a mixed-task block than on non-switch trials in single task blocks (in which just one task is completed). Finally, asymmetric switch costs have been reported in both paradigms such that switching into a more difficult task or less proficient language incurs smaller costs than switching into a less difficult task or more proficient language (for reviews see Kiesel et al., 2010; Declerck & Philipp, 2015). Functional neuroimaging studies also imply shared mechanisms (Abutalebi et al., 2012; Garbin et al., 2010; Abutalebi & Green, 2007, 2008; Ma et al., 2014); overlapping brain regions appear to support linguistic and non-linguistic task switching, most commonly the dorsolateral prefrontal cortex and the anterior cingulate (Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2015; de Baene et al., 2015; Garbin et al., 2010), and there is considerable overlap in brain regions activated specifically on switch trials in both domains (Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015).

Other evidence implies specialized mechanisms for language switching that are not shared with task switching. For example, Weissberger, Wierenga, Bondi, and Gollan (2012) found that aging bilinguals exhibited much greater difficulty with non-linguistic task switching than with language switching. Similarly, Calabria and colleagues (Calabria, Branzi, Marne, Hernández, & Costa, 2015) tested young, middle-aged and older Catalan-Spanish bilinguals and found an asymmetry in non-linguistic switch costs but not in linguistic switching for all age groups. They also found bigger switch costs in older than in young bilinguals in the non-linguistic task, but not in the linguistic task, and switching costs were not correlated across domains. These findings suggest minimal sharing between language control and executive control mechanisms (see also Gollan, Kleinman, & Wierenga, 2015; Gollan, Sandoval, & Salmon, 2011; Prior & Gollan, 2013). Indeed, Gollan et al., (2014) suggested that even when similar patterns are found, different underlying cognitive mechanisms might be involved. For example, switching costs are reduced in both domains when switches are voluntary instead of cued. However, only in the language task did the voluntary advantage appear to be driven by association of each stimulus with just one of two possible responses consistently throughout the mixed block (a "bottom up" responding strategy in which lexical accessibility drives switching behavior; Kleinman & Gollan, 2016).

More consistent with the shared mechanisms possibility, are reports that bilinguals sometimes outperform monolinguals on nonlinguistic control tasks (Baum & Titone, 2014; Bialystok, 2011; Costa & Sebastián-Gallés, 2014; Kroll & Bialystok, 2013; Valian, 2015 but see Duñabeitia et al., 2014; Hilchey, Saint-Aubin, & Klein, 2015). However, this topic is a matter of somewhat heated debate. Paap, Johnson, and Sawi (2016) suggested that the bilingual advantage is not well replicated and highly variable. On the other hand, a recent meta-analysis confirmed the bilingual advantage and reported moderate effect sizes (e.g., d = .30 in de Bruin, Treccani, & Della Sala, 2015). Though this gives reason to continue pursuing the question, meta-analyses, by their nature, gloss over small methodological differences across studies that may be critical for revealing when and where differences between groups can be detected. Such details are important not only for understanding the group differences themselves, but also for constraining the underlying theories that explain the behavior more generally in all populations.

Group Differences on the Color-Shape Task

On the possibility of a shared switching mechanism for linguistic and non-linguistic switching, the bulk of evidence accumulated to date comes from reports that bilinguals exhibit smaller switch costs than monolinguals, most often investigated using a switching task developed by Rubin and Meiran (2005) in which participants switch between judging color and shape based on a visually presented cue. Prior & MacWhinney (2010) were the first to report a bilingual switching advantage using this task. In their study, bilinguals exhibited an elite switcher pattern; they responded more quickly than monolinguals on *switch* trials, but not on other trial types, exhibiting smaller switch costs, and the same size mixing costs, as monolinguals. Garbin and colleagues (2010) also reported reduced errors on switch trials for bilinguals relative to monolinguals, but did not observe any group differences in RTs. Other studies also reported smaller switch costs for bilinguals, but did not conform to the elite switcher pattern. For example, in Prior and Gollan (2011) Spanish-English bilinguals responded more slowly than monolinguals, but slowing was larger on stay trials than on switch trials (significantly smaller after controlling for SES; see below). In the same study, Mandarin-English bilinguals did not differ from monolinguals in speed or the size of switch costs, and the bilinguals also reported that they switched languages significantly less often in daily life than did Spanish-English bilinguals. Interestingly, comparing these two bilingual groups in a *language switching* task, Spanish-English bilinguals exhibited significantly smaller switch costs relative to Mandarin-English bilinguals with a similar pattern (i.e., slowing on stay trials and in this case also faster responses on switch trials; see Figure 2 in Prior & Gollan, 2011). These results imply an association between language and task switching, and reveal some consistency in the tendency for bilinguals to respond more slowly on stay trials whether in a linguistic or non-linguistic task. Furthermore, they suggest that between group differences are caused by habitual language switching specifically, so that only bilinguals who switch languages frequently exhibit reduced switch costs.

This pattern of relative slowing for bilinguals on stay trials has been replicated in different parts of the world with different types of bilinguals. Garbin and colleagues (2010) found that early Spanish-Catalan bilinguals exhibited equally slow responses on switch and non-switch trials (no switching costs), whereas Spanish monolinguals responded more quickly on non-switch trials. Of note, Garbin et al., modified the color-shape task in a number of ways from its original form in part to accommodate neuroimaging protocols (e.g., there was no delay between cue and target; overlapping button-response mappings; written, instead of pictorial, task cues). Such modifications, though seemingly small, may in part be responsible for variation in findings obtained across studies. Table 1.1 summarizes methodological differences between studies that did versus did not find smaller switching costs for bilinguals relative to monolinguals using the color-shape task – a topic we return to in the General Discussion.

Most recently, de Bruin and colleagues (2015) compared older Gaelic-English bilinguals and monolinguals matched for multiple relevant factors (e.g., lifestyle, SES, education, IQ, gender, and age) on executive control tasks, including the color-shape task-switching paradigm. Bilinguals were divided into two groups including active versus inactive bilinguals—active bilinguals used both languages on a daily basis whereas inactive bilinguals mainly used English. Active bilinguals exhibited significantly and considerably smaller switching costs than monolinguals (almost four times smaller; 34 ms vs. 130 ms, respectively), while inactive bilinguals did not differ significantly from active bilinguals or monolinguals. Response times were equally fast overall for the three language groups, and active bilinguals were slightly but not significantly faster than monolinguals on switch trials, and slightly but not significantly slower than monolinguals on stay trials. De Bruin and colleagues also reported that between group differences in switching cost were no longer significant when switch costs were calculated as a proportion of overall speed. However, proportional adjustments for baseline speed might not be warranted when groups do not differ significantly in overall speed, and the finding of significantly reduced switching costs for active but not inactive bilinguals is in line with previous conclusions that some forms of bilingual language use lead to significantly smaller switch costs. However, failures to replicate the bilingual advantage in task switching have also been reported (Hernández, Martin, Barceló, and Costa, 2013; Paap & Greenberg, 2013; Paap et al., 2016; Paap & Sawi, 2014; Mor et al., 2015; Prior & Gollan, 2013).

A General Switch Mechanism?

The proposition that bilingual language use might lead to more efficient task switching rests on the assumption that there is a general switching mechanism. This is a question that itself is open to discussion. Some have suggested that set-shifting does not represent a global trait that can be captured by a single measure (Deák & Wiseheart, 2015). Of course, if there is no general switching mechanism, then frequent language switching could not possibly benefit task switching. Yehene and Meiran (2007) argued that there is a general switching ability but that not all switching tasks measure it equally well. They tested participants on two non-linguistic task switching paradigms, a shape/size judgment task and a vertical/horizontal task and also varied preparation time, or *cue-target interval (CTI)*, which was either short (116ms) or long (1016ms). A previous study showed strong correlations between switching costs at short and long cue-target interval (Friedman & Miyake, 2004), and thus, Yehene and Meiran (2007) aimed to explore whether this association remains across two different task switching paradigms which would support the notion of a general switch. Their criteria for general ability included a) shared variance across the two task switching paradigms, and b) shared variance with psychometric intelligence (which they also measured). Correlation analyses and structural equation modeling indicated that switching cost with a longer preparation time (i.e., a long CTI) as well as mixing cost, met these criteria; 37% and 15% of variance were shared across shape/size and vertical/horizontal tasks for switching and mixing costs, respectively. In contrast, switching cost with little preparation time (short CTI) was found to be paradigm-specific and did not meet their criteria for general switching ability. They concluded that general switching ability is best tapped by a switching cost with long preparation time.

It might seem surprising that switching costs with relatively short preparation time appeared to provide a weaker measure of task switching ability than costs with longer CTI, because greater preparation time might allow individuals with weaker executive control time to compensate for their weaknesses. However, Yehene and Meiran (2007) suggested that switching cost at short CTI may partly reflect the time needed to process the task cue, a task that might not be accomplished by the executive function system (Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Yehene & Meiran, 2007). On this view, switch costs with short CTI are contaminated by cue-processing abilities, in which case it is not surprising that they provide a less reliable measure of switching ability[1]. Interestingly, to date the majority

[1] Note that switch costs at short CTI are *not* completely unreliable, they just appear to be less reliable than mixing costs. Switching costs exhibited convergent validity even at relatively short CTIs in studies that examined factor loadings on a general shifting factor (with CTIs ranging from 0 to 150 ms; Friedman & Miyake, 2004; Klauer, Schmitz, Teige-Mocigemba, and Voss, 2010; Miyake & Friedman, 2012). Similarly, moderate correlations are found between different switching tasks (*r*s of .35 to .37; Friedman & Miyake, 2004). In studies with hundreds of participants (orders of magnitude more than typically tested in studies of the bilingual advantage) switch costs also exhibited good test-retest reliability even with relatively short CTI (Paap & Sawi, 2016), though note that in this

of studies that examined switching ability in bilinguals relative to monolinguals used a relatively short CTI (ranging from 0 ms to 250 ms; see Table 1.1) with the exception of a recent study that used a longer CTI (650 ms) that found a bilingual advantage in switching cost for elderly bilinguals (Houtzager et al., 2015). If Yehene and Meiran are correct that switch costs with short CTIs provide a poor measure of general switching ability, then it is perhaps not surprising that it has been difficult to replicate the bilingual advantage in task switching (which in turn should be more robust with a longer cue-target interval).

The Current Study

In this study, we tested the hypothesis that between group differences in task switching will be more apparent with a long than with a short CTI. We tested the same population of Spanish-English bilinguals that we previously reported exhibited smaller switching costs than monolinguals using the color-shape switching task (Prior & Gollan, 2011), and that was investigated in follow up studies (Prior & Gollan, 2013; Weissberger et al., 2012; Weissberger et al., 2015). We used a similar task and experimental design, but with a few modifications aimed at achieving a more robust signal. First, following the logic laid out by Yehene & Meiran (2007), we manipulated CTI including the same short (116 ms) or long (1016 ms) intervals used in that study. We hypothesized that if switch costs observed at long CTI offer a better reflection of general switching ability than at short CTI, and if bilingual language switching shares processes with switching in general, then differences between bilinguals and monolinguals should also be more robust at long CTI.

Also following Yehene and Meiran (2007), we included 320 mixed block trials, which is nearly twice as many trials as in Prior and MacWhinney (2010) and Prior & Gollan (2011; 2013). On the one hand, the increased number of trials might increase power for detecting between-group differences by creating a more reliable measure of switch costs. On the other hand, increasing the number of trials could

latter study mixing costs were considerably more reliable than switching (as in Yehene & Meiran, 2007 and see below).

reduce the advantage if, as outlined above, the mechanism of that advantage is transfer of practice from language switching. To address the latter possibility, we conducted separate analyses of the first and second half of experimental trials. Previous studies that examined practice effects in this way revealed inconsistent patterns; in one study monolinguals benefitted more from practicing a conflict-monitoring task than bilinguals, resulting in a bilingual advantage in the first block only (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009). Conversely, Abutalebi and colleagues (2011) found a reduced conflict effect with practice for bilinguals in a flanker task in the second of two testing sessions, whereas monolinguals did not show a reduction in conflict effects across testing sessions. In the present study, if between group differences in the magnitude of switching costs are found in the first half but not in the second half, this would be consistent with the hypothesis of transfer of practice from habitual language switching to nonlinguistic switching, that disappears when monolinguals accumulate extensive task-specific practice.

Finally, in addition to between group differences, we also looked within each language group at correlations between task switching and mixing costs at the two CTIs, and two standardized measures of task switching—the Trail Making Test and the Color-Word Interference Test (CWIT) to explore individual differences in switching ability as assessed by different measures. We also tested participants in a language switching protocol to more directly examine the hypothesis of shared control mechanisms (as in Prior & Gollan, 2011; 2013). For these analyses, significant correlations between costs across linguistic and nonlinguistic tasks would support the notion of a general switch and shared processing mechanisms across domains. To maximize comparability of linguistic and nonlinguistic switching, we restricted the number of stimuli to four digits (in previous studies we had nine), a manipulation that also made it possible to test monolinguals in our language switching paradigm (because monolinguals tested herein had enough exposure to a foreign language to name four digits). If only bilinguals exhibited cross-task correlations in switching costs, this would suggest that shared mechanisms for task and language control emerge only with extensive experience using two languages. Conversely, if significant correlations emerged even in monolinguals (who have little to no experience with language control), this would suggest that such effects are driven more by the nature of the tasks themselves than by patterns of language use and experience.

Methods

Participants

Eighty monolingual English speakers (76 right-handed) and eighty Spanish-English bilinguals (73 right-handed) who were undergraduates at the University of California, San Diego (UCSD) participated in the study for course-credit. A power analysis (G-Power; Faul et al., 2007) showed that the number of participants needed to achieve a small to medium effect size (as in previous literature) for a within-between interaction (for the factors of Trial Type and Group; 2 levels in each factor) using a repeated measures ANOVA with f = .24, power of 1-β = .90, and a two-tailed α = .01, with an average correlation of .7 among repeated factors, is *22 per group*. In addition, when deciding on sample size, with 80 participants per group we doubled the sample size of previous studies that included approximately 40 subjects (or less) per group (see Table 1.1), and had similar numbers of participants in each group as Yehene and Meiran, 2007 (n=98).

In the color-shape switching task, two participants (one bilingual, one monolingual) were excluded for having accuracy rates lower than 90% (which was 3.5 standard deviations below the mean for all participants). In the language-switching task, one bilingual was excluded for having an accuracy level lower than 93%, approximately 3 standard deviations lower than the mean for all bilinguals. Participants gave informed consent, and all study procedures were in accordance with the policies of the UCSD Institutional Review Board (IRB). Table 1.2 shows the characteristics of the participants' self-reported language history as well as demographic information. Bilinguals in the present study reported switching language often daily, and using Spanish often in their daily lives. San Diego is just 13 miles from the Mexican border, and opportunities to mix languages are plentiful. Many of the monolinguals tested herein had some formal training in Spanish or a different language (see Table 1.2), but primarily used English only throughout their lives. Thus, the monolinguals were not profoundly and purposefully purely monolingual—they had some exposure to Spanish or other languages either in school (see Table

1.2 for years of formal language training), or in the environment (e.g., many street names in San Diego are in Spanish), but they were clearly different from the bilinguals in their patterns of language use.

An important difference between bilinguals and monolinguals was that they were not matched on parent education level, often considered as a proxy for socioeconomic status (SES). Prior and Gollan (2011) hypothesized Spanish-English bilinguals' performance on the task-switching measure, though improved by their bilingualism, was also negatively affected by their lower SES relative to monolinguals. Supporting this view, bilinguals in that study exhibited significantly smaller switch costs than monolinguals only after matching for parent education level, and when controlling for response slowing by calculating proportionally adjusted switch costs relative to baseline (similar conclusions were reached using an ANCOVA with parent education level entered to control for SES and including all participants tested). Below we consider the possible role of parent education level in modulating group differences.

Materials and procedure

Participants completed one session of ~2 hours of testing consisting of cognitive and linguistic measures. Computerized tasks were presented using PsychoPy v1.83 (Peirce, 2008) on a Macintosh computer with a 20-inch color monitor. Response times for the non-linguistic task were collected with a response box. Naming times were recorded using headset microphones connected to a response box and were also recorded with a digital recorder. Participants were seated ~60 cm from the monitor. As commonly done in studies of individual differences (see Yehene & Meiran, 2007), all tasks were presented in the same testing order for all participants as follows. language history questionnaire, non-linguistic (color-shape) switching, linguistic (digit-naming) switching, Color-Word Interference Test (CWIT), Trail Making Test (TMT), and Multilingual Naming Test (MINT; in English only for monolinguals, in English then in Spanish for bilinguals). In the language-switching task, monolinguals were instructed to use whatever non-English language they could to name the four digits presented in the current study (for 66 monolinguals this was Spanish). We do not report these data in detail because our primary aim was to investigate between-group comparisons in the color-shape task, and because monolinguals would have had no real prior experience with language-switching, and without proficiency in a second language their performance would reflect different processing mechanisms not of interest here.

Color-shape task

This task was based on the design of the Shape/Size paradigm from Yehene and Meiran, 2007 (e.g., overlapping response buttons, randomized structure, number of trials in each block, cue-target interval) but some elements were modified to match the color-shape task from Prior & Gollan, 2011 and Rubin & Meiran, 2005; e.g., stimuli, ‘sandwich’ design). Participants made color and shape judgments on visually presented stimuli, using button presses to indicate their selection. The target stimuli were either red or green circles (3 cm radius) and triangles (3 cm base, 3 cm height). The task cue for the color task was a color gradient and the cue for the shape task was a row of small black shapes (7 cm by 2 cm). Cues were presented 3 cm above the position where the target stimulus would have been presented. Half of the participants were assigned to a response key combination in which “circle” and “green” responses were mapped to the right button box key, and “triangle” and “red” responses were mapped to the left button box key. The other half of the participants were assigned to a reversed response button combination in which “circle” and “red” were mapped to the right response button, while “triangle” and “green” were mapped to the left response button. To minimize working memory requirements, the response cues were displayed on the bottom left and right corners of the screen (e.g., instead of placement of stickers or a template onto the response box as done in Yehene & Meiran, 2007 and Prior & Gollan, 2011; see Weissberger et al., 2015).

Our use of overlapping button-response mappings is unlike most previous studies (see Table 1.1). With overlapping button-response mappings just two buttons are used and both tasks are represented by each button (e.g., one button is used for both “red” and “circle” responses, and the other button is used for “green” and “triangle” responses). This contrasts with non-overlapping button-response mappings, in which four different response buttons, and four different fingers are used to respond, with each different response mapped onto a separate button-finger combination. Interestingly, as summarized in Table 1.1, the few studies with overlapping mappings also found a bilingual advantage of some kind, either in mixing (Gold et al., 2013[2]. Experiments 1 & 2; Wiseheart, Viswanathan, & Bialystok, 2014) or in switching (Garbin et al., 2010 and the current study; see Hartanto et al., 2016 for review). Just one study with overlapping mappings did not find a bilingual advantage in behavioral data, but the color-shape task was modified substantially to accommodate neuroimaging (Rodríguez-Pujadas et al., 2013; they cued response rule initially with a written cue, and then subsequent trials were cued with "switch" or "repeat" instructions). Use of overlapping mappings may turn out to be important because it is arguably more similar to what bilinguals experience during language control and switching (i.e., bilinguals speak both of their languages out of one and the same the mouth). Overlapping mappings also increase task difficulty, via increased response competition (Gade and Koch, 2007), or demands on task-set reconfiguration (Meiran, Chorev, Sapir, 2000; Hartanto et al., 2016), which may increase the chances of observing group differences of various kinds (Hartanto et al., 2016; Wiseheart et al., 2014; Mayr, 2001).

Additionally, we used only one cue per task in previous studies that revealed reduced switch costs for bilinguals on the color-shape task. With just one cue per task, the effects of task-switching versus cue-switching are confounded (Logan & Bundesen, 2003), whereas use of two cues per task would make it possible to tease apart cue processing costs from task switching costs. However, additional cues can increase the working memory load, and therefore we avoided this modification in the interest of replicating previously observed differences between groups, and the possibility that working memory load might also modulate these differences.

Tasks were administered using a sandwich design (Rubin & Meiran, 2005) with one single task block, either color or shape, counterbalanced between subjects (80 trials), followed by four mixed task blocks, which had both color and shape decisions (80 trials, each), followed by one single task block, color or shape decisions (80 trials; whichever block was not completed initially). The single task blocks were counterbalanced such that half of the participants completed the color single block first, and the other half completed the shape single block first. Participants in Yehene and Meiran (2007) completed

[2] Note that some have interpreted these data as mixing costs (e.g., Hartanto & Yang, 2016) while others have interpreted this as a global switch cost (Wiseheart, Viswanathan, & Bialystok, 2014).

only one single task block following completion of four mixed task blocks. However, to equate power in switching and mixing cost analyses we had each participant complete single task blocks for both tasks, one before and one after the mixed blocks. Before the start of the mixed task blocks, participants were informed about the transition to the mixed task blocks in which they would perform two tasks, and then they completed 10 mixed task trials serving as practice. This counterbalancing procedure meant that tasks were practiced differently between subjects such that, for example, participants who completed the color task first may show smaller mixing costs for color than people who did not receive any practice with the color single block before completing the mixed blocks. However, we collapsed across individual tasks in our presentation of the results (see below), and an equal number of participants completed color first and shape first (counterbalanced) such that on average these differential practice effects should not be apparent in the analyses presented.

Participants were asked to respond as quickly and accurately as possible. Each trial began after a response in the previous trial and consisted of 1) a fixation crossed presented for 2032 ms, 2) the presentation of the task cue for either 116 or 1016 ms (which constituted our cue-target interval, or CTI manipulation) and remained on the screen until the target appeared and 3) the presentation of the cue and the target stimulus until the response was given, or for a maximum duration of 4 seconds, after which the fixation for the next trial began. The design of the mixed task blocks included 16 critical trial-types (with 2 task cues, 2 stimulus shapes, 2 colors of the stimulus, and 2 CTIs equally represented), which were randomly presented without replacement (within the 16 trials), and then repeated 5 times. All possible 16 trial types were presented at least once before another 16-trial 'miniblock' repeated. Additionally, the number of switch and stay trials was not constrained in order to follow the randomized nature of the design of Yehene & Meiran, 2007 (note that in Prior & Gollan, 2011 the number of stay and switch trials was equated by creation of fixed-lists). The fully-randomized presentation of trial types resulted in a switch rate of 53% (*SD* = 3%; range = 47-60%), for both monolinguals and bilinguals. Following Yehene and Meiran (2007) and Prior and Gollan (2011), in our primary analyses we collapsed color and shape decisions and thus had 160 single, approximately 160 stay, and 160 switch trials for each participant. As noted above, Prior and Gollan (2011) and Prior & MacWhinney, 2010, had about half as many stay and switch trials (n = 72), therefore, to facilitate comparison across studies, we present data separately for first versus second half of trials. Because of our counterbalancing procedure (some participants completed single color task blocks before and shape after mixed task blocks, and others vice versa) we did not divide single-task blocks into first and second halves, and thus the means for the single task trials reported below are identical for the first and second halves.

Language task

The design of the language task closely mirrored the non-linguistic task; all aspects of the design were the same with the exception of stimuli, task cues, and response type (i.e., voice recording versus button press). The stimuli in all blocks were four numbers (*two*, *five*, *eight*, and *ten*, which in Spanish are *dos, cinco, ocho, and diez*, respectively) and participants were asked to name the digit out loud as quickly and accurately as possible based on the language cue. The task cues were the American flag for English and the United Nations flag for Spanish. CTI and target presentation times were identical to those in the color-shape task. Participants first completed one single-language naming block (either in English or Spanish, counterbalanced across participants), followed by 10 trials of mixed task practice trials, 4 mixed language blocks, and one single-language naming block (English or Spanish, counterbalanced). As for the color-shape task, each block contained 80 trials, and the randomized presentation of trial type resulted in a 53% switch rate (*SD* = 3%; range. 47-59%).

Color-Word Interference Test

The Color-Word Interference Test (CWIT; Delis et al., 2001), an extension of the classic Stroop Test (Stroop, 1935) consists of four conditions comprised of 50 items each that are printed on a single page and placed in front of participants. Time in seconds to complete each condition was recorded for each participant. Baseline conditions assess lower-level functions and are composed of Color Naming (condition 1; naming color patches) and Word Reading (condition 2; reading color names printed in black ink). A third condition, Inhibition, assesses individuals' ability to inhibit the automatic tendency to read the word instead of naming the incongruent ink color (condition 3; e.g., say "blue" when the word “green” is printed in blue ink). The fourth condition, Inhibition/Switching, assesses individuals’ ability to switch (signaled by a line-drawn box around the stimulus) between naming the incongruent ink color (Naming condition 3) and reading a word (condition 2). In addition to completion times for each of the 4 conditions, Delis and colleagues (2001) provided contrast measures aimed at isolating certain aspects of executive functioning. These included (a) Inhibition Cost (Inhibition minus Color; is meant to reflect an individual’s inhibitory control ability while controlling for baseline color naming speed), (b) Inhibition/Switching Cost (Inhibition/Switching minus the sum of Naming and Reading; meant to reflect the ability to both inhibit and switch while controlling for baseline performance in both color naming and word reading), and (c) Switching Cost (Inhibition/Switching minus Inhibition; meant to reflect switching ability while controlling for inhibition ability).

Trail Making Test

The Trail Making Test (TMT. Reitan, 1992) has two conditions and measures individuals’ motor sequencing ability and the ability to flexibly switch between number and letter sequencing. Condition A consists of circles on a single 8 ½ x 11 inch page numbered from 1-25. Participants are asked to draw lines with a pencil to connect the numbers in ascending order as quickly and accurately as possible. In condition B, the circles include both numbers (1-13) and letters (A-L) and participants are asked to connect the circles in ascending order, but alternating between numbers and letters (e.g., 1-A-2-B). If the experimenter notices an error, s/he corrects the error by drawing two lines on the incorrectly drawn line and redirecting the participant to fix the error without pausing the stop-watch. Time in seconds to complete each condition was recorded for each participant.

MINT

The Multilingual Naming Test (MINT; Gollan et al., 2012) consists of 68 black-and-white line drawings, presented in increasing order of difficulty. Participants named the line drawings in English. Bilinguals subsequently named the same pictures in Spanish. The total number of pictures correctly named in each language provides a measure of language proficiency. This task was not timed.

Results

Color-Shape Task

Incorrect responses, responses immediately following an error, and responses slower than 3000 ms or faster than 300 ms, were excluded from the analysis (6% and 5% for bilinguals and monolinguals, respectively). All other responses were analyzed using SPSS 23. Table 1.3 shows means and standard deviations for all trial types for both groups. Figure 1.1 shows the results for each condition and participant group broken down by first (a) versus second (b) half of trials and represents only mixed block trials. Error rates in the mixed block of the color-shape task were low (M = 2.6%, SD =0.02; M = 3.1%, SD = 0.02 for bilinguals and monolinguals, respectively, which were not significantly different, p = .144). As such, we report detailed analyses of error rates only where these are critical for interpreting findings of key interest in the RTs. Additionally, Figure 1.2 shows error rates in each condition and half of trials for each participant group. In the mixed task blocks, responses were faster, and switching costs smaller, for color relative to shape responses, a main effect of Task, $F(1, 158) = 129.78$, $MSE = 22{,}397$, $p < .001$, $\eta^2 = .451$, and a significant interaction between Task and Trial Type, $F(1, 158) = 4.08$, $MSE = 6{,}475$, $p = .045$, $\eta^2 = .025$. However, there were no significant interactions between task and group, all Fs < 2.07, ps ≥ .15; thus, to maintain consistency with previous studies (Prior & Gollan, 2011, Prior & Gollan, 2013, Yehene & Meiran, 2007), and to simplify the presentation of the results, we collapsed across the task factor.

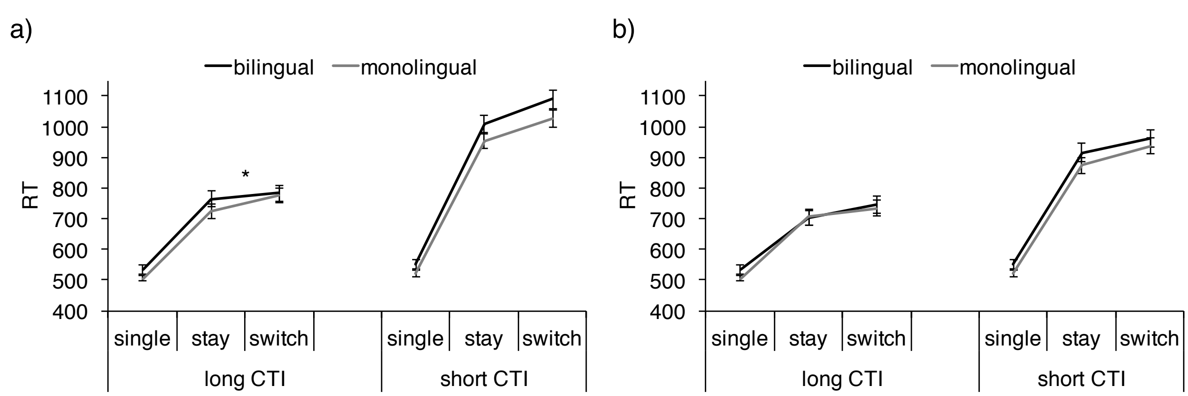

Figure 1.1. *Reaction times (in ms) for single, stay, and switch trials in the color-shape task shown for the first half (a) and second half (b) of experimental trials for both language groups. The asterisk denotes a significant difference in switching costs between the bilingual and monolingual groups at p < .05.*

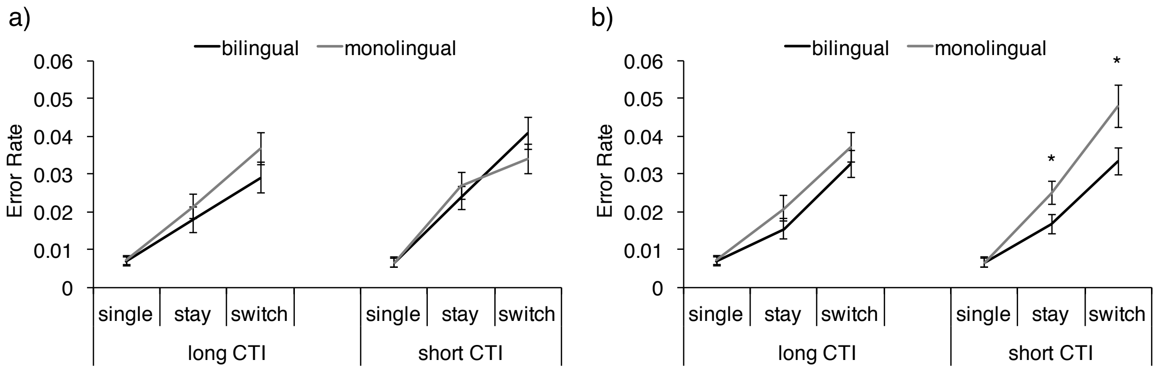

Figure 1.2. *Error rates (in % incorrect) for single, stay, and switch trials in the color-shape task for the first half (a) and second half (b) of the experimental trials for both language groups. Asterisks denote significant differences in error rates between the bilingual and monolingual groups at p < .05.*

Color-shape switching costs

To determine whether there were group differences in task switching efficiency, RTs for condition means in the color-shape task were entered into a four-way repeated measures analysis of variance (ANOVA) with language group as a between-subject factor (bilingual, monolingual), and three repeated measures factors including CTI (long, short), Trial Type (stay, switch), and Experimental Half (first, second). Foreshadowing the results briefly, the predicted 3-way interaction between CTI, Group, and Trial Type (switching costs) was not significant overall. However, there was a highly robust four-way interaction between CTI, Trial Type, Half, and Group, suggesting significantly smaller switch costs for bilinguals relative to monolinguals at long, but not short, CTI, but only in the first half of experimental trials. In the second half, there were no significant group differences at either long or short CTI. Below we report all main and interactions effects in order of complexity but refrain from interpretation of effects that are qualified by the four-way interaction.

Participants responded more quickly when the cue-target interval was long, a significant main effect of CTI, $F(1, 156) = 1293.37$, MSE =12,759, $p < .001$, $\eta^2 = .892$, more quickly when the task repeated versus on switch trials, a significant main effect of Trial Type, $F(1, 156) = 148.75$, MSE = 5,285, $p < .001$, $\eta^2 = .488$, and more quickly in the second than in the first half, evidencing practice effects, a significant main effect of Half, $F(1, 156) = 79.86$, $MSE = 18{,}994$, $p < .001$, $\eta^2 = .339$). There was no main effect of group ($F < 1$).

Group modulated CTI effects, a two-way interaction between CTI and language group, $F(1, 156) = 5.92$, $MSE = 12{,}759$, $p = .016$, $\eta^2 = .037$ (but see higher order interaction below). Follow-up contrasts revealed that both groups exhibited significant CTI effects (both ps $\leq .001$), such that response times were slower when participants had less time to prepare (i.e., in short than in long CTI), and looking within both long and short CTI, there were no significant group differences (ps $\geq .236$). Participants also benefitted more from practice at short than at long CTI, a significant interaction between CTI and Half, $F(1, 156) = 54.\ 40$, $MSE = 4{,}784$, $p < .001$, $\eta^2 = .259$. Replicating Yehene and Meiran (2007), switch costs were larger when participants had less preparation time, a significant interaction between CTI and Trial Type, $F(1, 156) = 13.31$, $MSE = 5{,}387$, $p < .001$, $\eta^2 = .079$. All other two-way interactions were not significant (ps $\geq .126$).

Participants responded more quickly with practice, especially at short CTI and on switch trials, a three-way interaction between CTI, Trial Type and Half, $F(1, 156) = 4.05$, $MSE = 2{,}970$, $p = .046$, $\eta^2 = .025$. All other three-way interactions were not significant (Fs <1).

To reveal the nature of the observed four-way interaction between CTI, Trial Type, Half, and Group ($F(1, 156) = 8.45$, $MSE = 2{,}970$, $p = .004$, $\eta^2 = .051$), we conducted 2 x 2 x 2 ANOVAs separately for long and short CTI[3]. At long CTI, bilinguals exhibited significantly smaller switching costs than

[3] To further examine the robustness of the four-way interaction, we conducted additional sensitivity analyses. Using Cook's Distance index to examine the impact of cases with undue influence on our findings, we identified eight participants exhibiting unusually large or negative switching costs. After removing these participants and repeating the repeated measures ANOVA, the four-way interaction remained significant. When excluding these 8 participants, the bilingual switching costs at long CTI in the first half was reduced to 10 ms (monolingual group's switching costs were 51 ms; $p = .003$; Cohen's $d = .48$). Finally, to determine if the four-way interaction was robust to multivariate ANOVA assumptions about model residuals (Maxwell & Delaney, 2004), we examined a mixed effects linear model with unstructured error matrix and obtained Bootstrap estimates of the model parameters based on 1,000 replications using Stata 14.1 [StataCorp, 2015]. The four-way interaction remained significant ($z = -2.90$, $p = .004$). In summary, because the bootstrap results are consistent with our original analyses, and because the Cook's Distance analyses did not suggest cases with undue influence, we interpret the four-way interaction to be statistically reliable and not an artifact of outliers or violations of statistical assumptions.

monolinguals, but only in the first half of experimental trials, a significant 3-way interaction between Trial Type, Half, and Group, $F(1, 156) = 7.22$, MSE =2,982, $p = .008$, $\eta^2 = .044$; in the first half, bilinguals exhibited only an 18 ms switching cost (SD = 109 ms), less than half that of monolinguals, which was 50 ms (SD = 76 ms), and a significant difference ($p = .036$; Cohen's $d = .34$), whereas in the second half, numbers trended non-significantly in the opposite direction (43 vs 28 ms switching costs for bilinguals and monolinguals respectively, $p = .203$). At short CTI, this 3-way interaction was not significant, $p = .214$); bilinguals and monolinguals exhibited similarly sized switching costs; at short CTI in the first half, switching costs for bilinguals and monolinguals were 81 and 72 ms, respectively ($p = .633$), and in the second half, switching costs for bilinguals and monolinguals were 45 and 62 ms, respectively ($p = .276$). Figure 1.3 shows switching and mixing costs for each group broken down by CTI and by half.

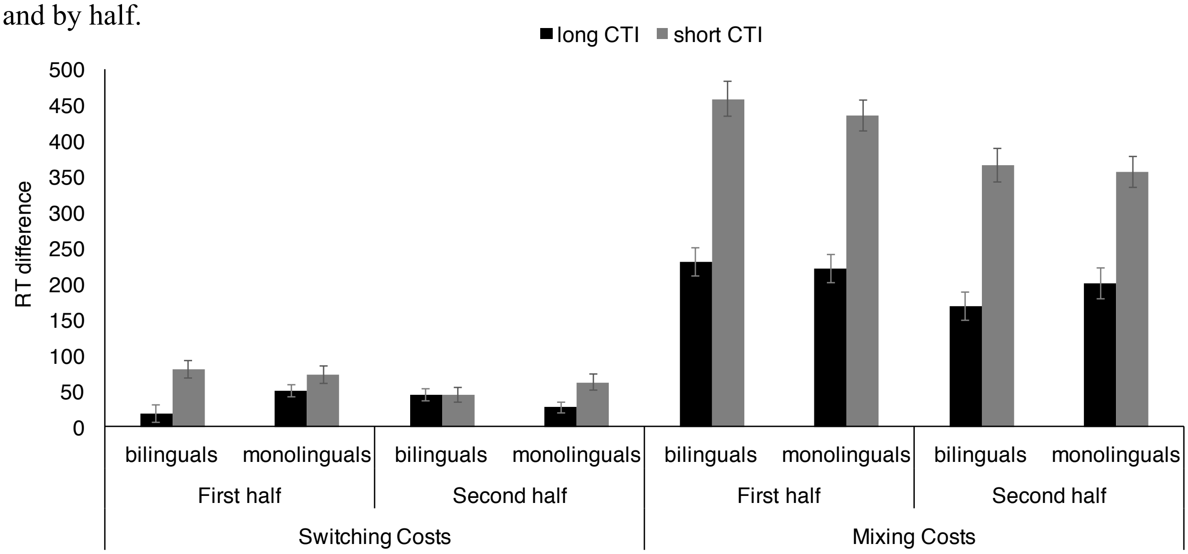

Figure 1.3. *Mean difference scores (i.e., switching and mixing costs in ms) broken down by first and second half of experimental trials for each CTI for both language groups*

Of note, the bilinguals' reduction in switching costs at long CTI in the first half of trials appeared as if it might be driven by slowed responses on stay trials relative to monolinguals (as in Prior & Gollan, 2011), or alternatively by faster performance on switch trials than expected for bilinguals given their tendency to respond more slowly in other conditions. Follow-up comparisons favored the latter interpretation. To test which trial type was critical for producing between group differences in switch costs in the first half, we conducted additional analyses to isolate stay versus switch responses. In general, in the mixed blocks, bilinguals tended to respond more slowly than monolinguals — this was most consistently apparent in the first half of trials (see Figure 1.1). Although this slowing in bilinguals was not significant (there was no main effect group), the means tended in that direction in 6 out of 8 group comparisons in the mixed blocks, with one critical exception, which was switch trials with long CTI in the first half. On these trials, bilinguals responded as quickly as monolinguals, and therefore relatively quickly (compared to themselves) given their tendency to respond more slowly in most other comparison points. The second exception was in the second half on stay trials with long CTI, but group differences in response speed in the second half were negligible, especially at long CTI (see Figure 1.1). Confirming this interpretation, when analyzing only switch responses, a 2-way ANOVA with CTI and Group as factors revealed a significant 2-way interaction, such that bilinguals responded slower than monolinguals on switch trials at short CTI trials, but no group differences on switch trials at long CTI, $F(1, 156) = 9.13$, $MSE = 59{,}757$, $p = .003$, $\eta^2 = .55$. Critically, when analyzing just stay trials, this same 2-way interaction was not significant, ($F < 1$). In these two analyses, matching those reported above, there were no main effects of group (ps $\geq .21$). Thus, it appears that switch trials, not stay trials, drove group differences in switching costs in the first half of the mixed block at long CTI; bilinguals' reduction in switching costs was driven by their relatively faster than expected for them performance on switch trials at long CTI. Additional analyses (presented in Supplemental Materials) illustrated consistency of these apparent patterns across the distribution of RTs (including slowest and fastest responses).

Switch costs in error rates. As noted above, we do not report detailed analyses of errors because participants committed very few errors overall. However, some consideration of errors is critical to ensure that the conclusions drawn were not driven by tradeoffs between speed and accuracy (or any tendencies in this direction). Thus, we repeated our four-way ANOVA, and the critical follow-ups with error rates, and error rates with an arcsine transformation (Winer et al., 1971). Results reported in detail are from untransformed data, and we mention analyses with arcsine transformation only where these produced different results than the untransformed data.

Briefly summarized, the four-way interaction reported above for RTs was just marginally significant in the error data (p = .083; and not significant after arcsine transformation, F<1). However, there was a significant 3-way interaction between Half, CTI, and Group (p = .006) such that bilinguals tended to be more accurate than monolinguals in every condition except in the first half at short CTI where bilinguals and monolinguals had equivalent in error rates. Additional 3-way ANOVAs with Half, CTI, and Trial Type conducted separately for each language group revealed that bilinguals significantly improved their accuracy with practice on short CTI trials, a significant 2-way interaction between Half and CTI ($F(1,78) = 4.20$, $MSE = .002$ $p = .030$, $\eta^2 = .059$). This same interaction was not significant in monolinguals (p = .120).

Most importantly, as shown in Figure 1.2, bilinguals tended to commit fewer errors than monolinguals on both stay and switch trials at long CTI (though not significantly so, ps ≥ .187), thus the relative advantage in switching costs could not be attributed to a speed-accuracy trade-off. The only condition in which bilinguals appeared to commit more errors than monolinguals was short CTI switch trials in the first half (though again this was not significant, p = .227), and by the second half bilinguals in fact committed significantly *fewer* errors than monolinguals in this same condition (p = .027; see Figure 1.2).

Summarizing the results for color-shape switch costs reported thus far, in the first half, bilinguals exhibited significantly smaller switch costs than monolinguals at long but not at short CTI. Similar to previous studies (Prior & Gollan 2011; de Bruin et al., 2015; Garbin et al., 2010) the bilinguals' reduction in switch costs appeared to reflect slower responses relative to monolinguals on stay trials. However, additional analyses instead implicated switch trials as being relatively faster for bilinguals at long CTI in the first half (when compared with themselves relative to monolinguals on other trial types as the baseline), and therefore switch trials as the critical trial type driving between group differences. Finally, both bilinguals and monolinguals tended to respond more quickly with practice, but only bilinguals also produced fewer errors with practice (at short CTI), whereas monolinguals did not become more accurate with practice.

Color-shape mixing costs

To examine between-group differences in mixing costs, we conducted another four-way repeated measures ANOVA but comparing responses in the single-task blocks with non-switch trials in the mixed blocks in the Trial Type factor (single block, mixed block-stay)[4]. Foreshadowing the results, although mixing costs appeared to provide a more consistent measure of individual differences in task performance than switching costs (a point that will be explained in detail below), we found no significant differences between bilinguals and monolinguals in these analyses (matching results reported by Prior & Gollan, 2011 and Prior & MacWhinney, 2010; see Table 1.1 for a summary of studies that found mixing cost differences between groups); the four-way interaction that was significant above in the analysis of switching costs was not significant in the analysis of mixing costs (F (1,156) = 1.69, MSE =3,690, p = .196, η^2= .01).

Participants responded more quickly at long than at short CTI, more quickly on single-block than on mixed block trials, and more quickly in the second than in the first half of trials; main effects of CTI, $F(1, 156) = 696.81$, $MSE = 5,959$, $p < .001$, $\eta^2 = .817$; Trial Type, $F(1, 156) = 488.52$, $MSE = 59,971$, $p < .001$, $\eta^2 = .758$, and Half, $F(1, 156) = 59.32$, $MSE = 5,441$, $p < .001$, $\eta^2 = .276$. The main effect of group was not significant, $F(1, 156) = 1.64$, $MSE = 188,359$, $p = .202$, $\eta^2 = .010$).

Replicating Yehene and Meiran (2007), participants exhibited larger mixing costs when they had less preparation time, a significant interaction between CTI and Trial Type, $F(1, 156) = 610.02$, MSE

[4] Note that single block RTs are identical for the first and second experimental halves because of the nature of the counterbalancing procedure (see Methods). However, the contrast between first versus second half nevertheless reveals how mixing costs change with practice.

=5,059, $p < .001$, $\eta^2 = .796$; participants responded more quickly with practice, but more so at short CTI, a significant interaction between CTI and Half, $F(1,156) = 18.36$, $MSE = 2{,}184$, $p < .001$, $\eta^2 = .105$; finally, mixing costs decreased in the second half of the experiment, a significant interaction between Trial Type and Half, $F(1,156) = 59.32$, $MSE = 5{,}441$, $p < .001$, $\eta^2 = .276$. All other two-way interactions were not significant (all *p*s ≥ .08).

Mixing costs decreased with practice, especially at short CTI compared to long, a significant three way interaction between CTI, Trial Type and Half, $F(1, 156) = 18.36$, $MSE = 2{,}184$, $p < .001$, $\eta^2 = .105$. All other three-way interactions did not reach significance (*p*s ≥ .09).

Summarizing these analyses, there were no between group differences in the magnitude of mixing costs. Looking within each language group separately, the results also appeared to be more similar than different. In monolinguals, mixing costs were significantly reduced in the second half of trials, and more so for short than for long CTI conditions, a significant interaction between CTI, Trial Type, and Half. $F(1, 78) = 19.53$, $MSE = 1{,}744$, $p < .001$, $\eta^2 = .200$. In bilinguals, mixing costs were also reduced in the second half, especially at short CTI; though in this case, the three-way interaction was only marginally significant, $F(1, 78) = 3.71$, $MSE = 2{,}623$, $p = .058$, $\eta^2 = .045$ (see Figure 1.3).

Language Task

Error rates in the mixed block for bilinguals in the language task were low ($M = 2.5\%$ $SD = 0.02$). Similar to the color-shape task, we do not report analyses of error rates in detail, but means and *SD*s by condition and half are shown in Table 1.4. RTs were trimmed using the same exclusion criteria as for the color-shape task (described above), which resulted in exclusion of 5.0% of the data. Figure 1.4 shows the results for each condition broken down by first (a) versus second (b) half of trials and contrasts language switching with color-shape switching performance. For reasons explained above, we did not report monolinguals' language switching data in detail. However, briefly summarizing their performance, monolinguals responded much more quickly in English than in whatever other language they used to name the 4 numbers used in the language switching task. Thus, despite massive repetition of just four number names in their non-English language, they, unlike the bilinguals tested in this study, exhibited strong language-dominance effects.

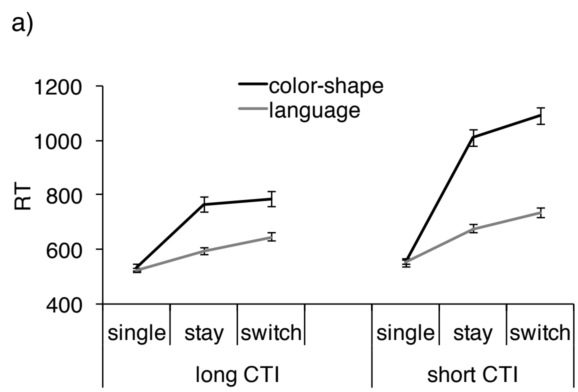

Figure 1.4. *Reaction times (in ms) for single, stay, and switch trials in the language task shown for the first half (a) and second half (b) of experimental trials for the bilingual group. Reaction times from the color-shape task are shown for comparison (same means as shown in Figure 1.1).*

Language switching costs

RTs for condition means were entered into a four-way repeated measures analysis of variance (ANOVA) with Experiment Half (first, second), Language Dominance (Dominant, Non-Dominant), CTI (long, short), and Trial Type (stay, switch), as repeated measures factors. Language dominance was determined by performance on the MINT; bilinguals with higher scores in English than in Spanish were classified as English-dominant (n = 73), one bilingual with equivalent English and Spanish scores was also classified as such because of immersion in an English dominant environment, and those with higher Spanish than English scores were classified as Spanish-dominant (n = 5). Importantly, the factor in these analyses was dominance, not language, and so this factor had the same number of subjects as all the others. For example, for English-dominant bilinguals, we classified all English responses as dominant and Spanish responses as non-dominant. Conversely, for Spanish-dominant bilinguals, all Spanish responses were classified as dominant and English responses as non-dominant. We collapsed across the language dominance factor in the figure because dominance did not interact significantly with the other conditions, with the exception of one marginally significant interaction that is mentioned briefly below.

Bilinguals exhibited significant switch costs ($M = 54$, $SD = 33$), responded more quickly at long than at short CTI ($M = 643$ vs. $M = 721$), and responded more slowly in the second than in the first half of experimental trials[5] ($M = 664$ vs. $M = 701$); main effects of Trial Type, $F(1, 78) = 200.92$, $MSE = 4{,}367$, $p < .001$, $\eta^2 = .720$; CTI, $F(1, 78) = 406.94$, $MSE = 4{,}781$, $p < .001$, $\eta^2 = .839$, and Half, $F(1, 78) = 45.16$, $MSE = 9{,}711$, $p < .001$, $\eta^2 = .367$. One of these effects marginally varied by language dominance, such that bilinguals responded more quickly at long CTI, but more so for dominant language responses, an interaction between CTI and Dominance, $F(1, 78) = 3.86$, $MSE = 1{,}345$, $p = .053$, $\eta^2 = .047$. All other interactions with language dominance were not significant (Fs ≤ 1.22, ps .27). Bilinguals responded more quickly in the first than in the second half, especially at the long CTI, a significant interaction between Half and CTI, $F(1, 78) = 7.14$, $MSE = 2{,}436$, $p = .009$, $\eta^2 = .084$. Notably, unlike the color-shape task, switch costs were not significantly smaller with long than with short preparation time, although the numbers trended in this direction, $F(1, 78) = 1.97$, $MSE = 2{,}249$, $p = .164$, $\eta^2 = .025$. No other interactions were significant (ps $\geq .360$). Our finding of faster responses with longer preparation time is consistent with other language switching studies that manipulated preparation time (Costa & Santesteban, 2004; Fink & Goldrick, 2015; Philipp, Gade, and Koch, 2007; but see Verhoef et al., 2009 who found no benefit of preparation on L1 stay trials). However, unlike some previous studies (as in Costa & Santesteban, 2004; Fink & Goldrick), we did not find that switch costs were reduced with longer preparation time.

The finding that responses slowed across experimental halves (with practice) was accompanied by a significant effect in the opposite direction in the error rates. Specifically, at long CTI, bilinguals produced significantly fewer errors with practice; this effect was significant on switch trials ($p = .001$), but not on stay trials ($p = .67$). Similarly, at short CTI, bilinguals tended to produce fewer errors in the

[5] This slowing of responses by the second half of the task could possibly be explained by general fatigue, as the language switching task was completed after the color-shape switching task.

second than in the first half on switch trials (p = .057), but not on stay trials (p = .110; see Table 1.4). Analyses with the arcsine transformed data revealed the same effects. Thus, in both linguistic and non-linguistic switching tasks, bilinguals exhibited some significant tendencies to improve their accuracy with practice especially on switch trials. However, this came with a cost in response times only in the language task, but note that this cost was very small; Figure 1.4 illustrates that in general the language task appeared to largely be at ceiling for bilinguals and changed very little with practice when compared with the color-shape task in which responses sped considerably across experimental halves.

Language mixing costs

Following our analyses of the color-shape task, we also carried out a four-way ANOVA with the same factors as in the switching costs analysis, but replacing switch trials with single task block responses in the Trial Type contrast. Bilinguals exhibited significant mixing costs (M = 116, SE = 9), responded more quickly when the CTI was long (M = 570, SE = 10), and more quickly in the first half of experimental trials; (M = 586, SE = 10); main effects of Trial Type, F (1, 78) = 190.96, MSE = 22,307, p < .001, η^2 = .710; CTI, F (1, 78) = 295.78, MSE = 2,916, p < .001, η^2 = .791, and Half, (F (1, 78) =43.53, MSE = 2,875, p < .001, η^2 = .358. A main effect of language dominance was marginally significant (F (1, 78) = 2.80, MSE = 5,887, p = .099, η^2 = .035, such that dominant-language responses were very slightly faster than non-dominant language responses (M = 593 vs. 600). Mixing costs generally did not vary by language dominance with the exception of one marginally significant 3-way interaction between dominance, CTI, and Trial Type, F (1, 78) = 2.96, MSE = 1,130, p = .090, η^2 = .036. As in the switching cost analyses, bilinguals responded more quickly in the first than in the second half, especially in the long CTI condition, a significant interaction between Half and CTI, F (1, 78) = 5.01, MSE = 1,128, p = .028, η^2 = .060. Bilinguals also exhibited larger mixing costs in the second part of the experiment, a significant interaction between Half and Trial Type, F (1, 78) = 43.53, MSE = 2,875, p < .001, η^2 = .358. Mixing costs were larger at short than at long CTI, a significant interaction between CTI and Trial Type, F (1, 78)

= 116.09, MSE = 1,375, $p < .001$, $\eta^2 = .598$. Finally, there was a larger CTI effect in mixing costs in the first than in the second half, a significant three-way interaction between Half, Trial Type and CTI, F (1, 78) = 5.01, MSE = 1,128, $p = .028$, $\eta^2 = .060$. No other interactions were significant (ps ≥ .408).

In summary, like the color-shape task, the language task exhibited significant interactions between CTI and costs, so that generally switching and mixing costs were larger when bilinguals had less preparation time, however this pattern was significant only for mixing costs. Additionally, in the language task bilinguals responded slightly more slowly with practice likely related to an accompanying and significant decrease in error rates with practice on switch trials with both long and short CTIs (whereas in the color-shape task RTs decreased with practice, and the reduction in error rates was found only at short CTI).

Association of Switching Costs Across Domains

The hypothesis of a general switch mechanism that serves both linguistic and non-linguistic switches predicts that switch costs should be correlated across domains. To investigate this possibility, we examined switching and mixing cost correlations between color-shape and language switching tasks, and for comparison we also included two other commonly used tests of switching ability (the Color-Word Interference test, or CWIT, and Trails A and B), and our objective measure of language proficiency (i.e., the MINT). To measure reliability of switch costs within each domain, we also correlated switching and mixing costs across long and short CTIs in each participant group within each task. Tables 1.5 and 1.6 show Pearson bivariate correlations between our primary experimental tasks for the bilinguals and monolinguals, respectively[6], and Figure 1.5 shows scatterplots for the main correlations of interest. After correcting for false discovery rate (FDR) in multiple comparisons using the Benjamini-Hochberg procedure (Williams, Jones, Tukey, 1999; Thissen, Steinberg, & Kuang, 2002) different cut-offs were determined for bilinguals and monolinguals by arranging p-values from lowest to highest and choosing

[6]We did not split the data into first and second halves for this analysis in part because the patterns observed were highly similar across halves, and because in the analysis of mixing costs only the stay trials vary with half (see Footnote 4).

the largest p-value that is smaller than the Benjamini-Hochberg critical value as threshold. We interpreted any effects significant at p of $\leq .009$ and $p \leq .006$, for bilinguals and monolinguals, respectively.

Of greatest interest was the possible relationship between color-shape and language tasks. In both subject groups, with mixing costs as the measure, these cross-domain correlations were moderately sized and statistically significant at both long and short CTI, whereas switch costs were not significantly correlated across domains (see Tables 1.5 and 1.6 and Figure 1.5 A-D). This same general pattern was found in the within-task correlations (i.e., contrasting long CTI with short CTI) – both bilinguals and monolinguals showed significant positive correlations with mixing costs as the measure, but not with switching costs (see Figure 1.5 E-F). To some extent, standardized clinical measures of switching ability (CWIT) exhibited the same general pattern; significant correlations between mixing costs, but not switching costs, in the color shape task and CWIT measures (see Tables 1.5 and 1.6)[7]. Although, the bilingual group displayed many more significant correlations with the CWIT than the monolinguals. Additionally, only the bilinguals showed robust correlations between mixing costs in the language task and the CWIT measures (these correlations were generally absent in monolinguals). In addition, in a previous study we found a bilingual advantage on the CWIT (Tao et al., 2015), but here we found only non-significant trends in this direction (see Table 1.2). Finally, measures of language proficiency (as measured by the MINT) were not correlated with mixing and switching costs. This too contrasts with findings by Tao and colleagues (2015), who found that higher English MINT scores predicted higher switching costs (as measured by the CWIT), while higher Heritage Language MINT scores predicted lower switching costs. However, caution is warranted in interpreting any between-study differences on these tasks because of prior completion of the color-shape task and the language-switching tasks in the present study.

[7] This might not be entirely unexpected, given that most CWIT measures make no attempt to separate mixing costs from switching costs, with the possible exception of the CWIT Switching Cost – though even here trial to trial performance may differ in important ways from block-wide performance on such tasks.

In summary, mixing costs in the color-shape task revealed multiple robust correlations within- and between tasks (with language switching and with other tests of switching ability in both bilinguals and monolinguals). In contrast, switching costs revealed few such correlations, and even when significant these tended to be smaller than correlations with mixing costs.

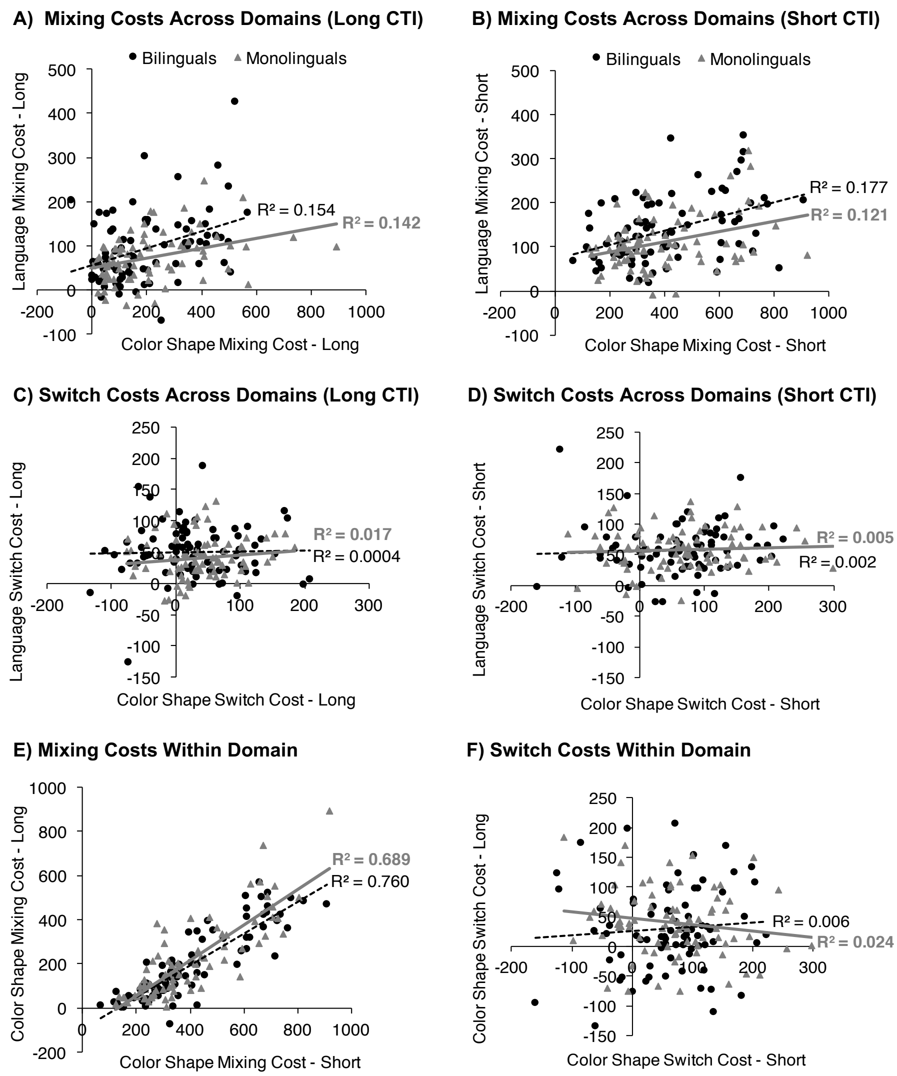

Figure 1.5. *Across-domain and within-domain correlations between color-shape and language tasks. Bilinguals' data shown in black dots and black lines, and monolinguals' data in gray triangles and gray lines.*

The Role of SES in Task Switching

As noted above, bilinguals in the present study likely had significantly lower SES than monolinguals as measured by average parental education. An important question that follows is would group differences in switching costs be more robust if controlling for the bilinguals' SES disadvantage?

In Prior and Gollan (2011), the bilinguals exhibited significantly smaller switch costs than monolinguals only after controlling for SES. Similarly, in past studies, SES appeared to modulate language group differences in executive functioning, both in children (Calvo & Bialystok, 2014; Carlson & Meltzoff, 2008) and adults (Paap et al., 2015 for review). In addition, studies in monolinguals have linked lower SES to poorer executive function mainly in children (Hackman et al., 2015; Hackman, Farah, Meaney, 2010 for review) but also in middle to late adulthood (Turrell et al., 2002).

In this respect, it is noteworthy that bilinguals in the present study did not respond more slowly than monolinguals (as in Prior & Gollan, 2011). This attenuates possible concerns that the previously reported result may have been spuriously caused by matching confounds (or a misguided approach to statistical analyses, contra suggestions of Paap, Johnson, & Sawi, 2015). The absence of significant response slowing in the present study for bilinguals, despite a clear SES disadvantage could suggest that bilingualism offsets the negative effects of SES on switching ability (Carlson & Meltzoff, 2008; Gollan et al., 2011), or alternatively that the task in the present study was less sensitive to SES effects than previous implementations of the task (e.g., Prior & Gollan, 2011; though the latter possibility seems unlikely given our discussion above concerning overlapping response mappings and task difficulty).

However, somewhat unexpectedly, in the present study monolinguals, but not bilinguals, showed a significant association between parent education level and task-switching costs (see Tables 1.5 and 1.6 and Figure 1.6). Monolinguals with more educated parents exhibited smaller switching and mixing costs at long CTI ($r = -.24$; $p = .032$ and $r = -.30$, $p = .008$) and smaller mixing costs at the short CTI ($r = -.38$, $p = .001$; but not switching cost, which unexpectedly exhibited a difficult to interpret positive correlation between parent education level and switch costs at short CTI, $r = .32$, $p = .004$). In contrast, and even though bilinguals had parents with much more variable education levels, and far lower levels of education than monolinguals (see Table 1.2, and black dots in Figure 1.6), there were no significant correlations in the bilingual group between parent education level and switching or mixing costs at either long CTI ($r = .19$, $p = .09$ and $r = -.08$, $p = .48$, for switching and mixing costs, respectively) or short CTI ($r = .02$, $p = .88$ and $r = -.11$, $p = .33$, for switching and mixing costs, respectively; see Figure 1.6).

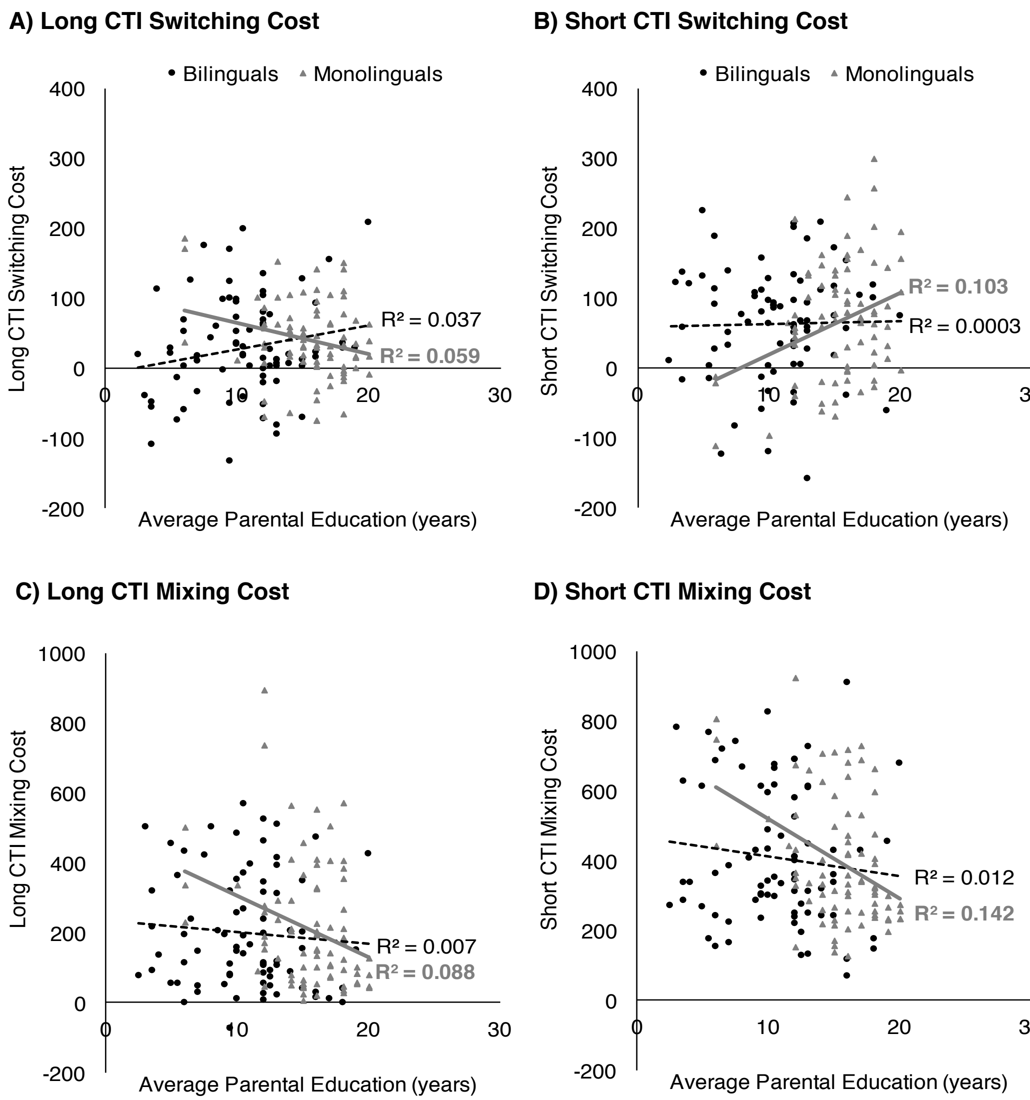

Figure 1.6. *Correlations between socio-economic status (SES, as measured by average parental education) and switching and mixing costs in the color-shape task by language group. Bilinguals' data shown in black dots and black lines, and monolinguals' data in gray triangles and gray lines.*

General Discussion

The present study investigated the existence of a general switch mechanism that might be used by bilinguals to control when and how they switch between languages. Critically, following suggestions of Yehene & Meiran (2007) and others (Logan & Bundesen, 2003; Mayr & Kliegl, 2003), we assumed a distinction between cue processing and switch mechanisms, and manipulated preparation time to obtain a purer measure of switching abilities. Specifically, we hypothesized that extending preparation time (by using a longer cue-target interval) would reduce contamination of switch costs by cue processing times (which should not differ between bilinguals and monolinguals), thus revealing more robust between group differences in switching ability (a cognitive mechanism that might be expected to benefit from bilingual language use).

A Shared General Switch Mechanism

As predicted, bilinguals exhibited significantly smaller switch costs than monolinguals when allowed to prepare to switch with the longer CTI, and no analogous between-group difference in switching costs were found with short preparation time. Importantly, the bilinguals' switch cost advantage appeared to be driven by their relatively faster performance on switch trials on which they responded as quickly as monolinguals, whereas in other conditions bilinguals tended to respond slightly but not significantly more slowly than monolinguals. On this view, bilinguals responded faster on switch trials with preparation and prior to extensive practice than expected relative to themselves when compared with monolinguals on other trials in the first half of the mixed-block (a pattern that appeared to be highly consistent across the distribution of RTs; see Supplemental Material).

Though error rates were very low overall in the present study, the hypothesis of a general switch mechanism that may be improved by bilingual language use, was generally consistent with the pattern of results found in the error data. Mostly importantly, there was no evidence that bilinguals committed more errors than monolinguals in the same condition that revealed a bilingual advantage (see Figure 1.2); i.e., on switch trials at long CTI in the first half, if anything bilinguals tended to be more accurate than monolinguals. Additionally, by the end of the experiment monolinguals increased their speed without any change in accuracy, bilinguals sped up in the responses and either maintained their tendencies towards higher accuracy than monolinguals (at long CTI), or were significantly more accurate than monolinguals (at short CTI in the second half; see Figure 1.2).

Additionally, bilinguals exhibited reduced switching costs only in the first half of the experiment, which is consistent with the idea that switching ability can improve with practice – a requirement for the hypothesis that bilingual advantages reflect increased practice with switching and transfer from language switching to general switching ability. Previous studies have also reported fleeting bilingual advantages (e.g., Costa et al., 2009) which could imply that whatever transfers from language control to benefit nonlinguistic control (switching in the present study) will pale in comparison with task-specific practice. This is not very surprising given the many differences between how bilinguals use their two languages in daily life and a necessarily limited relationship to how switching is measured in the lab, provided that task-specific switching mechanisms exist and can also benefit from practice. At minimum, the present results suggest that practice effects can modulate between group differences and should be examined (none of the studies shown in Table 1.1 considered practice effects).

Our interpretation of these data is consistent with previously proposed suggestions of a bilingual advantage in switching (Garbin et al., 2010; Houzager et al., 2015; Prior & MacWhinney, 2010; Prior & Gollan, 2011), and the proposal of a general switch mechanism, and builds on these notions in a number of ways. As noted briefly above, the finding that the bilingual advantage disappears with practice implies that task-specific switch mechanisms exist or develop, and that these domain-specific mechanisms are more powerful than the general switch mechanism and transfer between domains. Furthermore, the observation of a bilingual advantage only at long but not short CTI has additional implications. One view of these findings is that bilinguals are better specifically at switching per se, but they cannot prepare to switch better than monolinguals can (i.e., bilinguals are only better at switching once fully prepared to do so). However, an alternative possibility with a very different underlying cognitive mechanism is that bilinguals switch more efficiently only when given ample time to prepare. On this view, bilinguals are not better at switching per se, but are better able to take advantage of preparation time – meaning they are better than monolinguals at preparing to switch (see Hernández et al., 2013 for possibly related discussion of bilingual advantages in more complex switching tasks).

Yehene & Meiran's (2007) suggestion that switching ability is better measured at long CTI seems more consistent with the first possibility, however either explanation appears to be equally adequate for interpreting the group differences reported herein.

Aspects of the Data that Appear to be Inconsistent with a Shared General Switch Mechanism

Other aspects of our data seem inconsistent with the idea of a shared general switch mechanism. In particular, bilinguals did not respond more quickly than monolinguals on switch trials (for discussion see Wagenmakers, 2015; Hilchey et al., 2015) – though our analysis above implicates switch trials as critical. Additionally, though bilinguals exhibited a disadvantage in socioeconomic status (SES, as measured by parental education level), and though SES appeared to modulate group differences in previous work (Prior & Gollan, 2011), no such pattern emerged with respect to SES in the present study. Switching costs were not robustly correlated with SES in either bilinguals or monolinguals in the present study, and mixing costs were significantly reduced by higher SES only in monolinguals (see Figure 1.6, Tables 1.5 and 1.6). Possibly critical differences relative to previous studies include our manipulation of CTI and overlapping button-response mappings in the present study. Both of these manipulations arguably make the task more difficult, and overlapping button-response mappings seem critical given our review of the literature in Table 1.1. Increased task-difficulty might make it easier to observe beneficial effects of bilingualism which might in some circumstances undo or minimize negative effects of very low SES on switching and mixing costs for this group. Importantly, under this interpretation, better matched groups of bilinguals and monolinguals might not necessarily reveal more consistent between group differences (particularly if matched groups removed all participants with very low SES).

Perhaps the greatest challenge to both the general-switch mechanism, and shared-switch, hypotheses, was our failure to observe robust correlations between switching costs across task-switching and language-switching (see Tables 1.4 and 1.5; Figure 1.5). The total absence of significant correlations here would seem to be at odds with the notion of a general switch mechanism used in both language switching and task-switching, and perhaps best measured at long CTI (assuming Yehene & Merian, 2007 were correct that these pinpoint switch processes more specifically). To further investigate the absence of cross-domain correlations in switch costs, we combined bilingual and monolingual participants and recalculated cross-domain correlations collapsing together all 160 participants, as well as Spearman-Brown boosted split-half reliabilities comparing odd versus even blocks. The latter revealed significant correlations between odd and even blocks in switching costs at both long CTI ($r = .29$) and short CTI ($r = .31$, both ps $< .05$) in the color-shape task (see also Friedman & Miyake, 2004; Yehene & Meiran, 2007; Paap & Sawi, 2016), and in the language task (both rs $= .37$; ps $< .01$). Critically cross-domain correlations remained not significant even with all subjects combined (rs $< .10$).

However, our observation of robust correlations in mixing costs across-domains for both bilinguals *and* monolinguals, imply some significant limitations in the use of such correlations to test the hypothesis of shared control mechanisms.

Failures to Replicate the Bilingual Switching Advantage

The current analysis suggests that failed attempts to replicate the originally reported bilingual switching advantage (Prior & MacWhinney, 2010) should be attributed to relatively low reliability of switch cost measures, and the use of relatively short CTIs in the majority of these attempts. Additional, and possibly equally or even more important considerations include the use of non-overlapping button-response mappings, failure to consider practice effects, and failure to incorporate analysis of accuracy (which can be especially problematic in studies of individual differences; Hughes et al., 2014; Friedman & Miyake, 2004; Friedman et al., 2006; Miyake et al., 2000). Error rates, even if very low overall, may be deemed irrelevant without good reason (see Table 1.1 for summary of studies that did not report error analyses). In the current study, even at high levels of accuracy we found some significant effects in accuracy measures (see Figure 1.2). The bilingual switching advantage may also be restricted to, or more likely to appear in, bilinguals who switch languages frequently or active bilinguals (e.g., de Bruin et al., 2015; Hartanto & Yang, 2016; Prior & Gollan, 2011; Verreyt et al., 2015). These factors add to a long and rapidly growing list that might be critical to consider in future studies including variation in types of bilinguals studied, methodological differences in tasks, sample sizes, and approach to analysis (Paap, 2014; Paap & Sawi, 2014; for review see Paap, 2016), and even differing interpretations of relatively similar data patterns (compare de Bruin et al., 2015[8] versus Prior & Gollan, 2011).

[8] De Bruin et al., (2015) found significantly smaller switch costs for bilinguals than for monolinguals but argued against the notion of a bilingual advantage, because bilinguals tended to respond more slowly (albeit not

Another critical issue when measuring switching ability is reliability of the switching measures, and the extent to which they do or do not measure how switches, both linguistic and nonlinguistic, are planned and executed in daily life. Indeed, our finding of significant cross-domain correlations in mixing costs in monolinguals suggests substantial limitations on the extent to which the tasks used in the present study measure what bilinguals do to control activation of their two languages in daily life. Bilinguals' ability to juggle two languages involves many cognitive processes that are not captured by these type of switching tasks.

In our study, standardized clinical measures of switching ability also did not exhibit strong correlations with trial-to-trial task switching (and were instead better correlated with mixing costs; see Tables 1.5 and. 1.6). Some CWIT measures were correlated with language mixing costs in bilinguals but not in monolinguals, perhaps implying some cross-domain transfer but not in a manner that leads bilinguals to consistently perform better on the CWIT (see Tao et al., 20105; but see Table 1.2) or mixing in general. Together these considerations suggest that better measures of both switching ability, and what ties those measures very specifically to what individuals do in daily life will be useful if they can be developed (perhaps along lines suggested by Green & Abutalebi, 2013; Hartanto & Yang, 2016; Yang, Hartanto, & Yang, 2016; Verreyt et al., 2015; Festman & Münte, 2012).

Why is the Group Difference in Switching but not Mixing Costs?

Our finding of robust correlations between mixing costs across domains (see also Prior & Gollan, 2013) implies overlap in the cognitive mechanisms underlying task-mixing and language-mixing and

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significantly), and because when switch costs were calculated proportional to overall speed, the between-group difference in switch costs was no longer significant. In the current study, bilinguals did not respond significantly more slowly than monolinguals on the color-shape task. To match de Bruin et al's analysis, when we did control for baseline speed by calculating proportional switching cost (difference between switch and stay trials/stay trials * 100) our bilinguals exhibited a proportional switching cost that remained significantly smaller than that of monolinguals ($p = .02$) at long CTI in the first half of trials, consistent with the non-adjusted analyses. As in the current study, de Bruin et al., found that bilinguals tended to respond more slowly than monolinguals on stay trials, a pattern which led them to suggest that between-group differences might have reflected a difference in response strategy. Indeed, given the number of studies that have now reported this pattern, along with Prior & Gollan's (2011) report of a similar pattern in the language switching task for Spanish-English relative to Mandarin-English bilinguals, it might seem that bilingualism elicits a generally more cautious approach to mixed-task blocks. However, we offered a different interpretation in the present study based on separate examination of group comparisons on switch versus stay trials. Such comparisons might be further informative when trying to understand between group differences.

raises questions regarding why we did not observe a bilingual advantage in mixing costs. An important consideration here is that mixing costs appear to be more reliable than switching costs in both linguistic and non-linguistic switching paradigms. In the present study, mixing costs were also often significantly correlated with other measures, and others have reported higher test-retest reliability for mixing than switching costs in the color-shape task (Paap & Sawi, 2016). Indeed, perhaps it is not so surprising to find that that between-block differences appear to be more stable and reliable than within-block differences—mixing costs in the color-shape task are typically larger than switching costs (Rubin & Merian, 2005; but see Experiment 3 of Hernández et al., 2013). Additionally, as noted above, the finding that mixing costs were correlated across domains to the same extent in monolinguals as in bilinguals, implies that whatever overlap exists in control mechanisms used across tasks should not be attributed to bilingual language use. Thus, the absence of a bilingual advantage in mixing might simply reflect the fact that the tasks used herein do not adequately measure cross-domain transfer in mixing ability (assuming that such transfer does occur). This interpretation raises additional questions when considered in concert with our above interpretations of the switching advantage for bilinguals. Specifically, either cross-domain transfer in switching ability is stronger than cross-domain transfer in mixing, or the same tasks that measure cross-domain transfer in switching ability nevertheless do not measure cross-domain transfer in mixing ability – which seems a bit ad hoc.

In fact, some have suggested that mixing costs is where one would most expect bilingual advantages to arise—given that actual switches are relatively rare events, but the possibility to need to mix languages is always present when bilinguals are speaking (Prior & Gollan, 2013; Wiseheart et al., 2014; Bialystok et al., 2009 for review). Following this logic, Barac and Bialystok (2012) used the color-shape switching task with three groups of six-year old bilingual children (Chinese-English, French-English, and Spanish-English) and found smaller mixing, but not switching, costs for all bilingual groups relative to monolingual children. Possibly related, using language-switching to train color-shape switches and vice versa, Prior and Gollan (2013) found cross-domain transfer in mixing, but not switching, costs. On a related note, Soveri and colleagues (2011) found that a higher frequency of bilingual every-day language switching was related to a smaller *mixing* (but not switching) cost in errors on a number-letter switching task. Soveri and colleagues suggested that mixing cost reflects top-down management of two competing tasks, and thus closely resembles an everyday conversation in which a bilingual must decide which language to use by recruiting sustained control and general monitoring processes (although note that this finding was not replicated in a similar follow-up study from the same group; Jylkkä et al., 2017).

With the exception of the study by Barac and Bialystok (2012) and Gold and colleagues (2013), most of the color-shape switching studies that modeled Rubin & Meiran (2005) have not found a bilingual advantage in mixing (see Table 1.1). However, Wiseheart and colleagues (2014) hypothesized that the bilingual advantage should be in mixing costs in tasks that elicit interference between stimulus-response mappings. Thus, they used a paradigm in which stimulus-response mapping was changed on every trial (i.e., 100% response incompatible trials; see also Cepeda, Kramer, & Gonzalez de Sather, 2001). Specifically, in their study, the responses ‘blue’ and ‘horse’ were always indicated with the left index finger, and responses ‘red’ and ‘cow’ always with the right index finger. Additionally, only blue cows and red horses were presented as stimuli (no red cows and no blue horses); therefore, correct responding in this task required active updating of stimulus response associations on each and every switch trial (whereas in most switching studies with overlapping button response mappings a correct response could be produced 50% of the time for the wrong reason, i.e., even if a participant failed to switch tasks).

Most previous studies comparing bilinguals and monolinguals on task switching used non-overlapping responses with 50% of trials being response incompatible (see Table 1.1). Only a few studies used overlapping responses and also used 50% response incompatible trials (i.e., for half the trials the stimulus is associated with a different response; Garbin et al., 2010; Gold et al., 2013; the current study). Wiseheart and colleagues speculated that Gold and colleagues’ finding of a mixing advantage for older adults may be explained by the fact that older adults are most sensitive to remapping and thus may show an advantage even with a 50% response incompatibility rate, whereas for a bilingual advantage in younger adults, a higher rate of response incompatible trials may be required (as found in their study). In future studies, it may be useful to vary the proportion of incompatible trials to see if this modulates how bilingualism influences performance in switching paradigms.

Greater consideration of possible points of overlap between linguistic and non-linguistic task switching where between domain transfer in control mechanisms might be most likely to occur might also be helpful. That is, what aspect of bilingual language use might benefit performance on a color-shape switching task given that these are obviously much more different than they are similar? It has been suggested that mixing costs reflect global conflict monitoring (Koch, Prinz, & Allport, 2005; Los, 1996, 1999), whereas switching costs reflect task reconfiguration, and the ability to inhibit the previous task in order to activate the currently relevant task (Meiran et al., 2000; Meuter, 2005; Monsell, 2003; Prior & MacWhinney, 2010; Prior & Gollan, 2013; Rubin & Meiran, 2005).

Initiation of some types of language switches might not involve domain-general mechanisms whatsoever (e.g., Kleinman & Gollan, 2016; Gollan & Goldrick, 2016; submitted). In the linguistic domain, languages are also naturally competing responses, whereas features such as color or shape are usually not in competition. Potential for overlap may come from the need in both domains to disengage from a prior task in order to engage with the new task, or from anticipating the need to switch when different cues are present (though in naturalistic settings the cues themselves would of course be very different, e.g., a person's face, a red or green traffic light). The present results suggest that preparation to switch might be an important factor mediating cross-domain transfer in control mechanisms, and that besides switching itself, other processes might ultimately be implicated (including preparation/planning, monitoring, in addition to switching itself). But the absence of bilingual advantage in mixing, and the absence of consistent advantages in switching, remain a bit of a mystery at this point in time.

Concluding remarks

Investigation of bilingual advantages in task switching was triggered by the assumed existence of a general switching ability, and the possibility of transfer between linguistic and nonlinguistic processing domains, as well as a perhaps implicit assumption that frequent switchers should exhibit characteristics potentially associated with "elite" switching ability. However, the pursuit of such ideas can easily and quickly be misleading, carrying with them untested assumptions that may or may not be correct. Here we found evidence for switching ability as a skill that improves with practice, and ample preparation time may allow this general ability (as well as its role in both task and language switching) to be revealed in trial-to-trial switching as measured in the lab with experimental control. Paradoxically, practice reduced switching costs the most with*out* ample preparation time (i.e., at short CTI), thus further work remains to be done to explore how preparation time, practice, and cross-domain transfer might interact (specifically, it is not clear that task-specific practice and cross-domain transfer should be explained in the same way; see also Prior & Gollan, 2013). Expectations that highly practiced switchers should be advantaged especially on switch trials can also be misleading, and must be considered relative to an appropriate baseline, with joint consideration of error rates, and other factors that may introduce between group differences. A pattern that by direct comparison seems to implicate one condition in explaining between groups differences, might be viewed differently when performance is considered across different trial types within each group. As a field, development of measures that are more clearly tied to naturally occurring experience with greater specification of what exactly should improve with practice will likely be fruitful both for understanding bilingual language control and more broadly for understanding task switching and multi-tasking.

References

Abutalebi, J., & Green, D. (2007). Bilingual language production. The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*, 242–275.

Abutalebi, D. J., & Green, D. W. (2008). Control mechanisms in bilingual language production. Neural evidence from language switching studies. *Language and Cognitive Processes*, *23*, 557–582.

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S., & Costa, A. (2011). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex, 22*, 2076–2086.

Barac, R., & Bialystok, E. (2012). Bilingual effects on cognitive and linguistic development. role of language, cultural background, and education. *Child Development*, *83*, 413–422.

Baum, S., & Titone, D. (2014). Moving toward a neuroplasticity view of bilingualism, executive control, and aging. *Applied Psycholinguistics, 35*, 857-894.

Bialystok, E. (2011). Reshaping the mind. The benefits of bilingualism. *Canadian Journal of Experimental Psychology*, *65*, 229–235.

Bialystok, E., Craik, F.I.M., Green, D.W., & Gollan, T.H. (2009). Bilingual minds. *Psychological Science in the Public Interest, 10,* 89–129.

Branzi, F. M., Della Rosa, P. A., Canini, M., Costa, A., & Abutalebi, J. (2015). Language control in bilinguals. Monitoring and response selection. *Cerebral Cortex*, 1–14. doi.10.1093/cercor/bhv052

Calabria, M., Branzi, F. M., Marne, P., Hernández, M., & Costa, A. (2015). Age-related effects over bilingual language control and executive control. *Bilingualism. Language and Cognition*, *18*, 65–78.

Calvo, A., & Bialystok, E. (2014). Independent effects of bilingualism and socioeconomic status on language ability and executive functioning. *Cognition*, *130*, 278–288.

Carlson, S. M., & Meltzoff, A. N. (2008). Bilingual experience and executive functioning in young children. *Developmental Science*, *11*, 282–298.

Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. C. (2001). Changes in executive control across the life span. examination of task-switching performance. *Developmental Psychology*, *37*, 715–730.

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing. Now you see it, now you don't. *Cognition*, *113*, 135–149.

Costa, A., & Santesteban, M. (2004). Lexical access in bilingual speech production. Evidence fro language switching in highly proficient bilinguals and L2 learners. *Journal of Memory and Language, 50,* 491–511.

Costa, A., & Sebastián-Gallés, N. (2014). How does the bilingual experience sculpt the brain? *Nature Reviews Neuroscience*, *15*, 336–345.

Deák, G. O., & Wiseheart, M. (2015). Cognitive flexibility in young children. General or task-specific capacity? *Journal of Experimental Child Psychology*, *138*, 31–53.

De Baene, W., Duyck, W., Brass, M., & Carreiras, M. (2015). Brain circuit for cognitive control is shared by task and language switching. *Journal of Cognitive Neuroscience*, *27*, 1752–1765.

de Bruin, A., Bak, T. H., & Della Sala, S. (2015). Examining the effects of active versus inactive bilingualism on executive control in a carefully matched non-immigrant sample. *Journal of Memory and Language*, *85*, 15–26.

Declerck, M., & Philipp, A. M. (2015). A review of control processes and their locus in language switching. *Psychonomic Bulletin & Review*, *22*, 1630–1645.

Delis, D.C., Kaplan, E., & Kramer, J.M. (2001). Delis-Kaplan Executive Function System (D-KEFS) examiner's manual. San Antonio, TX. The Psychology Corporation.

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited. myth or reality? *Experimental Psychology*, *61*, 234–251.

Faul, F., Erdfelder, E., Lang, A.G., & Buchner, A. (2007). G*Power. a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191.

Festman, J., & Münte, T. F. (2012). Cognitive control in Russian-german bilinguals. *Frontiers in Psychology*, *3*, 1-7.

Fink, A., & Goldrick, M. (2015). Pervasive benefits of preparation in language switching. *Psychonomic Bulletin & Review*, *22*, 808–814.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions. a latent-variable analysis. *Journal of Experimental Psychology. General*, *133*, 101–135.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., Defries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science*, *17*, 172–179.

Gade M., Koch I. (2007). The influence of overlapping response sets on task inhibition. *Memory & Cognition. 35*, 603–609.

Garbin, G., Sanjuan, A., Forn, C., Bustamante, J. C., Rodriguez-Pujadas, A., Belloch, V., Hernandez, M., Costa, A., & Avila, C. (2010). Bridging language and attention. brain basis of the impact of bilingualism on cognitive control. *NeuroImage*, *53*, 1272–1278.

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., & Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *Journal of Neuroscience*, *33*, 387–396.

Gollan, T.H., & Goldrick, M (submitted). A switch is not a switch. Syntactically-driven bilingual language control.

Gollan, T. H., Kleinman, D., & Wierenga, C. E. (2014). What's easier. doing what you want, or being told what to do? Cued versus voluntary language and task switching. *Journal of Experimental Psychology. General*, *143*, 2167–2195.

Gollan, T. H., Sandoval, T., & Salmon, D. P. (2011). Cross-language intrusion errors in aging bilinguals reveal the link between executive control and language selection. *Psychological Science*, *22*, 1155–1164.

Gollan, T. H., Weissberger, G. H., Runnqvist, E., Montoya, R. I., & Cera, C. M. (2012). Self-ratings of spoken language dominance. A Multilingual Naming Test (MINT) and preliminary norms for young and aging Spanish–English bilinguals. *Bilingualism. Language and Cognition*, *15*, 594–615.

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism. Language and Cognition*, *1*, 67–81.

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals. The adaptive control hypothesis. *Journal of Cognitive Psychology*, *25*, 515–530.

Hackman, D. A., Farah, M. J., & Meaney, M. J. (2010). Socioeconomic status and the brain. mechanistic insights from human and animal research. *Nature Reviews. Neuroscience*, *11*, 651–659.

Hackman, D. A., Gallop, R., Evans, G. W., & Farah, M. J. (2015). Socioeconomic status and executive function. developmental trajectories and mediation. *Developmental Science*, *18*, 686–702.

Hartanto, A., & Yang, H. (2016). Disparate bilingual experiences modulate task-switching advantages. A diffusion model analysis of the effects of compound bilingualism on switch costs. *Cognition*, *150,* 10-19.

Hernández, M., Martin, C. D., Barceló, F., & Costa, A. (2013). Where is the bilingual advantage in task-switching? *Journal of Memory and Language*, *69*, 257–276.

Hilchey, M. D., Saint-Aubin, J., & Klein, R. M. (2015). Does bilingual exercise enhance cognitive fitness in non- linguistic executive processing tasks? *Cambridge Handbook of Bilingual Processing*. Cambridge. CUP.

Houtzager, N., Lowie, W., Sprenger, S., & de Bot, K. D. (2015). A bilingual advantage in task switching? Age-related differences between German monolinguals and Dutch-Frisian bilinguals. *Bilingualism. Language and Cognition*, 1–11.

Hughes, M. M., Linck, J. A., Bowles, A. R., Koeth, J. T., & Bunting, M. F. (2014). Alternatives to switch-cost scoring in the task-switching paradigm. their reliability and increased validity. *Behavior Research Methods*, *46*, 702–721.

Jylkkä, J., Soveri, A., Wahlström, J., Lehtonen, M., Rodríguez-Fornells, A., & Laine, M. (2017). Relationship between language switching experience and executive functions in bilinguals. an Internet-based study. *Journal of Cognitive Psychology*, 1–16.

Kiesel, A., Steinhauser, M., Wendt, M., Falkensten, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching. A review. *Psychological Bulletin, 136*, 849-874.

Klauer, K.C., Schmitz, F., Teige-Mocigemba, S., Voss, A. (2010). Understanding the role of executive control in the Implicit Association Test. Why flexible people have small IAT effects. *The Quarterly Journal of Experimental Psychology, 63*, 595-619.

Kleinman, D., & Gollan, T. H. (2016). Speaking two languages for the price of one. Bypassing language control mechanisms via accessibility-driven switches. *Psychological Science, 27,* 700-714.

Koch, I., Prinz, W., & Allport, A. (2005). Involuntary retrieval in alphabet-arithmetic tasks. Task-mixing and task-switching costs. *Psychological Research*, *69*, 252–261.

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology, 25*, 497-514.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus. Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology. Human Perception and Performance*, *29*, 575–599.

Los, S. A. (1996). On the origin of mixing costs. Exploring information processing in pure and mixed blocks of trials. *Acta Psychologica*, *94*, 145–188.

Los, S. A. (1999). Identifying stimuli of different perceptual categories in mixed blocks of trials. Evidence for cost in switching between computational processes. *Journal of Experimental Psychology. Human Perception and Performance*, *25*, 3–23.

Ma, H., Hu, J., Xi, J., Shen, W., Ge, J., Geng, F., Wu, Y., Guo, J., & Yao, D. (2014). Bilingual cognitive control in language switching. An fMRI study of English-Chinese late bilinguals. *PLoS ONE*, *9*, 1-8.

Maxwell, S. E. and Delaney, H. D. (2004). Designing experiments and analyzing data. a model comparison perspective. Lawrence Erlbaum Associates, Mahwah, N.J., 2nd edition.

Mayr, U. (2001). Age differences in the selection of mental sets. The role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging*, *16*, 96–109.

Mayr, U., & Kliegl, R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *29*, 362–372.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology*, *41*, 211–253.

Meuter, R. (2005). Language selection in bilinguals. Mechanisms and processes. In J.F. Kroll & De Groot, A.M.B Eds. Handbook of Bilingualism. Psycholinguistic approaches, New York, NY, Oxford University Press, pp 349-370.

Meuter, R., & Allport, A. (1999). Bilingual language switching in naming. Asymmetrical costs of language selection. *Journal of Memory and Language, 40*, 25-40.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions. Four general conclusions. *Current Directions in Psychology, 21*, 8–14.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” t asks. a latent variable analysis. *Cognitive Psychology*, *41*, 49–100.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*, 134–140.

Mor, B., Yitzhaki-Amsalem, S., & Prior, A. (2015). The joint effect of bilingualism and ADHD on executive functions. *Journal of Attention Disorders*, *19*, 527–541.

Myers-Scotton, C. M. (2006). Natural codeswitching knocks on the laboratory door. *Bilingualism. Language and Cognition*, 9, 203–212.

Paap, K. R. (2014). The role of componential analysis, categorical hypothesising, replicability and confirmation bias in testing for bilingual advantages in executive functioning. *Journal of Cognitive Psychology*, *26*, 242–255.

Paap, K.R. (2016). The neuroanatomy of bilingualism. will winds of change lift the fog? *Language, Cognition and Neuroscience, 31*, 331-334.

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*, 232–258.

Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex, 69*, 265–278.

Paap, K.R., Myuz, H.A., Anders, R.T., Bockelman, M.F., Mikulinsky, R., & Sawi, O.M. (2016). No compelling evidence for a bilingual advantage in switching or that frequent language switching reduces switch cost. *Journal of Cognitive Psychology, 29,* 89-112.

Paap, K. R., & Sawi, O. (2014). Bilingual advantages in executive functioning. problems in convergent validity, discriminant validity, and the identification of the theoretical constructs. *Language Sciences*, *5*, 962.

Paap, K.R., & Sawi, O. (2016). The role of test-retest reliability in measuring individual and group differences in executive functioning. *Journal of Neuroscience Methods, 274,* 81-93.

Peirce, J. W. (2008). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, *2*, 1-8.

Philipp, A. M., Gade, M., & Koch, I. (2007). Inhibitory processes in language switching. Evidence from switching language-define response sets. *European Journal of Cognitive Psychology, 19*, 395–416.

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers. evidence from Spanish-English and Mandarin-English bilinguals. *Journal of the International Neuropsychological Society*, *17*, 682–691.

Prior, A., & Gollan, T. H. (2013). The elusive link between language control and executive control. A case of limited transfer. *Journal of Cognitive Psychology*, *25*, 622–645.

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism. Language and Cognition*, *13*, 253–262.

Reitan, R.M. (1992). Trail Making Test Manual for administration and scoring. South Tucson, AZ. Reitan Neuropsychology Laboratory.

Rodríguez-Pujadas, A., Sanjuán, A., Ventura-Campos, N., Román, P., Martin, C., Barceló, F., Costa, A., & Ávila, C. (2013). Bilinguals use language-control brain areas more than monolinguals to perform non-linguistic switching tasks. *PLoS ONE*, 8, 1-8.

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *31*, 1477–1491.

Soveri, A., Rodriguez-Fornells, A., & Laine, M. (2011). Is there a relationship between language switching and executive functions in bilingualism? Introducing a within-group analysis approach. *Frontiers in Psychology*, *2*, 1-8.

StataCorp. 2015. *Stata Statistical Software. Release 14*. College Station, TX. StataCorp LP.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643.

Tao, L., Taft, M., & Gollan, T. H. (2015). The bilingual switching advantage. Sometimes related to bilingual proficiency, sometimes not. *Journal of the International Neuropsychological Society*, *21*, 531–544.

Thissen, D., Steinberg, L., & Kuang, D. (2002). Quick and easy implementation of the Benjamini-Hochberg procedure for controlling the false positive rate in multiple comparisons. *Journal of Educational and Behavioral Statistics*, *27*, 77–83.

Turrell, G., Lynch, J. W., Kaplan, G. A., Everson, S. A., Helkala, E.-L., Kauhanen, J., & Salonen, J. T. (2002). Socioeconomic position across the lifecourse and cognitive function in late middle age. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *57*, S43–51.

Valian, V. (2015). Bilingualism and cognition. *Bilingualism. Language and Cognition*, *18*, 3–24.

Verhoef, K., Roelofs, A., & Chwilla, D. J. (2009). Role of inhibition in language switching. Evidence from event-related brain potentials in overt picture naming. *Cognition, 110,* 84–99.

Verreyt, N., Woumans, E., Vandelanotte, D., Szmalec, A., & Duyck, W. (2016). The influence of language-switching experience on the bilingual executive control advantage. *Bilingualism. Language and Cognition*, *19*, 181–190.

Wagenmakers, E.J. (2015). A quartet of interactions. *Cortex*, *73*, 334–335.

Weissberger, G. H., Gollan, T. H., Bondi, M. W., Clark, L. R., & Wierenga, C. E. (2015). Language and task switching in the bilingual brain. Bilinguals are staying, not switching, experts. *Neuropsychologia*, *66*, 193–203.

Weissberger, G. H., Wierenga, C. E., Bondi, M. W., & Gollan, T. H. (2012). Partially overlapping mechanisms of language and task control in young and older bilinguals. *Psychology and Aging*, *27*, 959–974.

Williams, V. S. L., L. V. Jones, and J. W. Tukey. (1999). “Controlling Error in Multiple Comparisons, with Examples from State-to-State Differences in Educational Achievement. *Journal of Educational and Behavioral Sciences*, *24*, 42–69.

Winer BJ, Brown DR, Michels KM. Statistical principles in experimental design. New York. McGraw Hill; 1971.

Wiseheart, M., Viswanathan, M., & Bialystok, E. (2014). Flexibility in task switching by monolinguals and bilinguals. *Bilingualism. Language and Cognition*, *19*, 141–146.

Yang, H., Hartanto, A., & Yang, S. (2016). The complex nature of bilinguals' language usage modulates task-switching outcomes. *Frontiers in Psychology*, *7*, 1-8.

Yehene, E., & Meiran, N. (2007). Is there a general task switching ability? *Acta Psychologica*, *126*, 169–195.

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Table 1.1. *Summary of Behavioral and fMRI Studies Using the Color-shape Switching Task to Explore a Bilingual Advantage*

Study	Participants	AoA	Use patterns	No. of trials	CTI	Response mapping	Error analyses	Switching cost	Mixing cost
Prior and MacWhinney (2010)	Bilinguals (15 different languages; $N = 47$) Monolinguals ($N = 45$)	≤6	Used other language 27% of the time	288 total (144 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	No difference	Bilingual advantage	No difference
Garbin et al. (2010) - fMRI	Spanish-Catalan bilinguals ($N = 19$) Spanish monolinguals ($N = 21$)	≤4	Not reported	60 trials total (30 mixed-switch, 30 mixed-stay)	0 ms	Overlapping	Bilingual advantage	Bilingual advantage	N/A
Prior and Gollan (2011)	Spanish-English bilinguals ($N = 41$) Mandarin-English bilinguals ($N = 43$) Monolinguals ($N = 47$)	≤6	Used other language 13–15% of the time; Spanish-English switch more frequently than Mandarin-English	288 total (144 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	No difference	Relative switching cost advantage in Spanish-English bilinguals when controlled for SES	No difference
Gold et al. (2013) fMRI-Experiment 1	Older bilinguals (8 different languages; $N = 15$) Older English monolinguals ($N = 15$)	≤10	Not reported	240 trials (80 single-stay, 80 mixed-switch, 80 mixed-stay)	150 ms	Overlapping	No difference	Bilingual advantage[a]	
Gold et al. (2013) fMRI-Experiment 2	Older adult bilinguals ($N = 20$) Younger adult bilinguals ($N = 20$) Older adult monolinguals ($N = 20$) Young adult bilinguals ($N = 20$)	≤10	Not reported	240 trials (80 single-stay, 80 mixed-switch, 80 mixed-stay)	150 ms	Overlapping	No difference	Older adult bilingual marginal advantage in proportional switching cost[b]	
Hernandez et al. (2013)-Experiment 3	Catalan-Spanish bilinguals ($N = 38$) Monolinguals ($N = 39$)	≤4	Used other language 25% of the time	288 total (144 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	No difference	No difference	No difference
Paap and Greenberg (2013)	Bilinguals (~30 different languages; $N = 109$) Monolinguals ($N = 144$)	≤6	Used other language 28% of the time	288 total (144 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	No difference	No difference	No difference
Rodríguez-Pujadas et al. (2013) - fMRI[c]	Catalan-Spanish bilinguals ($N = 18$) Spanish monolinguals ($N = 18$)	≤4	Used other language 41% of the time)	70 trials (35 mixed-stay and 35 mixed-switch)	0 ms	Overlapping	No difference	No difference	N/A
Paap and Sawi (2014)	Bilinguals (16 different languages; $N = 58$) Monolinguals ($N = 62$)	N/A	Used other language 30% of the time	288 total (144 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	Not reported	No difference	No difference

Table 1.1. *Summary of Behavioral and fMRI Studies Using the Color-shape Switching Task to Explore a Bilingual Advantage…Continued*

Study	Participants	AoA	Use patterns	No. of trials	CTI	Response mapping	Error analyses	Switching cost	Mixing cost
Mor et al. (2015)	Russian Hebrew bilinguals with ADHD (N = 20) Russian Hebrew bilingual controls (N = 20) Hebrew monolinguals with ADHD (N = 20) Hebrew monolinguals controls (N = 20)	~6	Not reported	288 trials total (144 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	Bilingual controls were less accurate on incongruent trials than monolingual controls	No difference	No difference
Wiseheart, Viswanathan, and Bialystok (2016)[d]	Bilinguals (19 different languages; N = 31) Monolinguals (N = 37)	N/A	Used other language 52% of the time	150 total (50 single-stay, 50 mixed-switch, 50 mixed-stay)	0 ms	Overlapping	No difference	No difference	Bilingual advantage
de Bruin, Bak, and Della Sala (2015)	Gaelic-English older bilinguals-active (N = 28) Gaelic-English older bilinguals-inactive (N = 24) English monolinguals (N = 24)	5	Active bilinguals used both languages regularly	216 total (72 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	Not reported	Bilingual advantage in switching costs for active bilinguals; no difference between overall RTs and proportional costs	No difference
Houtzager, Lowie, Sprenger, and de Bot (2015)	Middle-aged and elderly Dutch-Frisian bilinguals (N = 25 in each age group) Middle-aged and elderly German and English monolinguals (N = 25 in each age group; most monolinguals spoke German but 2 spoke English)	≤6	Bilinguals used both languages on a daily basis since AoA	192 total (96 single-stay, 48 mixed-switch, 48 mixed-stay)	650 ms	Nonoverlapping	Not reported	Bilingual advantage in switching cost for elderly bilinguals only	No difference
Paap et al. (2016)	Bilinguals (21 different languages; N = 122 Monolinguals (N = 108)	6	Not reported	288 total (144 single-stay, 72 mixed-switch, 72 mixed-stay)	250 ms	Nonoverlapping	No difference	No difference	Marginal monolingual advantage that was not significant when using efficiency score
Current study	Spanish-English bilinguals (N = 79) Monolinguals (N = 79)	≤4	Used other language 18% of the time	480 total (160 single-stay, ~160 mixed-switch, ~160 mixed-stay)[e]	116 and 1016 ms	Overlapping	No group differences in first half; bilingual error advantage in second half for all trial types at short CTI	Bilingual advantage in switching costs only in first experimental half, at 1016 ms CTI	No difference

[a] In this study, the authors did not distinguish between mixing and switching costs in their analyses. [b] This difference was marginally significant and the authors computed proportional switching costs in order to account for age-related slowing. [c] While the task involves color-shape switching, the design of this study was significantly altered in comparison to the other color-shape switching studies. [d] Barac and Bialystok (2012) used the same color-shape switching task with bilingual children of three different language combinations and found (a) all three bilingual groups displayed faster response times than the monolingual group and (b) smaller mixing, but not switching costs, for all bilingual groups relative to monolingual children. [e] Because of the randomized nature of the design, on average there were slightly more switch trials than stay trials (53% switch rate; see Methods). Therefore, the number of mixed-switch and mixed-stay trials vary by individual (SD = .03).

Table 1.2. *Means and Standard Deviations of Participant Characteristics and Performance on Executive Function Tasks, and Statistics for Group Comparisons*

Variable	Bilinguals $N = 79$ (65 females)		Monolinguals $N = 79$ (64 females)		Significance test	
	M	*SD*	*M*	*SD*	*t*	*p*
Age	20.3	2.1	20.6	1.8	1.20	.23
Self-rated English proficiency (1–7)	6.5	.7	6.9	.1	2.44	<.001
Spanish or other language proficiency (1–7)	5.9	.8	1.6	.8	—	—
% English daily use currently	82.4	15.8	99.1	2.4	10.52	<.001
% English daily use when growing up	51.9	17.8	97.8	4.0	35.91	<.001
How often switch languages currently (1- *almost never*, 5-*constantly*)	3.7	1.3	N/A		—	—
Years of formal foreign language study	4.3	2.9	3.7	2.1	1.53	.13
Months lived abroad	24.9	51.0	.6	2.9	4.23	<.001
Average caregiver yrs education	10.6	3.9	15.5	3.0	9.70	<.001
Age of first exposure to English (yrs)	3.3	2.6	.1	.4	12.71	<.001
MINT (English)	60.7	3.5	64.4	2.2	8.86	<.001
MINT (Spanish)	47.6	9.3	N/A		—	—
Trails A	21.9	6.7	22.9	7.6	<1	.36
Trails B	51.9	15.9	48.7	12.4	1.38	.17
Trails B/A	2.5	.9	2.3	.6	1.76	.08
CWIT 1 (color name)	28.9	4.2	27.5	4.5	2.05	.04
CWIT 2 (word read)	20.5	3.2	21.0	3.8	<1	.36
CWIT 3 (inhibition)	44.7	9.6	43.0	8.5	1.16	.25
CWIT 4 (inhibition/switching)	49.0	9.1	49.2	8.2	<1	.89
CWIT inhibition cost	15.8	8.3	15.6	7.9	<1	.85
CWIT inhibition/switching cost	−.5	7.9	.8	8.7	<1	.36
CWIT switching cost	4.2	7.3	6.2	8.0	1.63	.11[b]

Note. MINT= Multilingual Naming Test.
[a] There were no significant group differences in the Trail Making Test and in most of the subsets of the Color Word Interference Test (CWIT) with the exception of the 'switching cost' measure of the CWIT, which revealed some tendencies in the predicted direction. [b] Bilinguals tended to exhibit smaller switch costs than monolinguals (4.2 versus 6.2 ms; although this difference was not significant using a one-tailed t-test, $t(78) = 1.96$; $p = .053$. This result is in the same direction but less robust than that reported by Tao et al. (2015), but it is important to consider that participants in the current study received *considerable practice* with trial-to-trial switching tasks prior to completing the CWIT. These practice effects could have differentially affected the groups' performance (indeed within the color-shape task alone we observed significant between group differences in how performance changed with practice, and both groups subsequently also completed trial to trial language switching prior to completing the CWIT).

Table 1.3. *Mean RTs and Standard Deviations in the Color-Shape Switching Task for both Language Groups*

Experiment trials	CTI	Trial type	Bilinguals		Monolinguals	
			M	*SD*	*M*	*SD*
All trials	Long	Single	534	117	505	83
	Short	Single	551	121	520	91
First half	Long	Stay	766	231	726	212
		Switch	784	232	776	211
	Short	Stay	1,009	270	955	235
		Switch	1,090	265	1,027	236
	Long	Switching cost	18	109	50	76
	Short	Switching cost	81	107	72	111
	Long	Mixing cost	232	177	221	173
	Short	Mixing cost	459	209	435	192
Second half	Long	Stay	703	227	706	232
		Switch	747	247	734	221
	Short	Stay	916	280	875	229
		Switch	961	247	937	239
	Long	Switching cost	43	77	28	72
	Short	Switching cost	45	89	62	98
	Long	Mixing cost	169	175	201	192
	Short	Mixing cost	365	211	355	191

Note. CTI = cue–target interval.

Table 1.4. *Mean Error Rates and Standard Deviations in the Language Switching Task for Bilinguals*

			Bilinguals		
Block type	Experiment trials	CTI	Trial type	*M*	*SD*
Single task	All trials	Long	Single	.002	.006
		Short	Single	.003	.006
Mixed task	First half	Long	Stay	.017	.027
			Switch	.046[a]	.032
		Short	Stay	.013	.022
			Switch	.034*	.035
	Second half	Long	Stay	.014	.025
			Switch	.032[b]	.034
		Short	Stay	.008	.016
			Switch	.023*	.030

Note. Means in the same column with different superscript letters differ from each other significantly at $p < .01$. Means in the same column with asterisks differ from each other marginally significantly at $p = .06$.

Table 1.5. *Bivariate Correlations among Tasks for Bilingual Participants*

	Color-shape				Language			
	Switching costs		Mixing costs		Switching costs		Mixing costs	
Task	Long	Short	Long	Short	Long	Short	Long	Short
Color-shape: SC long	—							
Color-shape: SC short	.079	—						
Color-shape: MC long	*−.201*	*−.263*	—					
Color-shape: MC short	*−.014*	*−.410**	**.872***	—				
Language: SC long	.020	.050	−.007	−.010	—			
Language: SC short	.248	.046	−.019	.140	.313*	—		
Language: MC long	.026	−.133	**.392***	**.379***	*.020*	*.189*	—	
Language: MC short	−.082	−.194	**.394***	**.421***	*.107*	*.086*	**.887***	—
Average parent education	.193	.017	−.081	−.111	−.203	−.178	−.063	−.125
CWIT color name	−.011	−.212	.274	**.412***	.124	.295*	**.391***	**.439***
CWIT reading	.019	−.205	.154	.250	.102	.248	**.414***	**.412***
CWIT inhibition	−.026	−.091	**.381***	**.436***	.150	.155	**.425***	**.510***
CWIT inhibition/switching	−.028	−.049	.264	.298*	.035	.081	**.464***	**.497***
CWIT inhibition cost	−.024	.003	.300*	.293*	.110	.028	.291	**.365***
CWIT inhibition/switching cost	−.034	.141	.093	.019	−.068	−.167	.155	.168
CWIT switch cost	−.002	.058	−.172	−.202	−.153	−.103	.018	−.052
Trails A	−.221	−.012	.251	.292*	−.036	.128	.182	.247
Trails B	−.139	.052	.273	**.345***	.066	.091	.075	.056
Trails B/A	.135	.110	−.087	−.045	.015	.025	−.135	−.209
MINT English	.087	−.231	−.018	−.053	−.060	−.104	.059	.078
MINT Spanish	.071	−.096	.133	.068	−.079	.072	−.092	−.071

Note. Italicized are correlations that violate independence. SC = Switching costs; MC = Mixing costs; CWIT = Color Word Interference Test; MINT = Multilingual Naming Test.

* Correlation is significant at $p \leq .009$ (FDR-corrected); bolded = correlation is significant at $p \leq .003$ (Bonferroni-corrected).

Table 1.6. *Bivariate Correlations among Tasks for Monolingual Participants*

	Color-shape				Language			
	Switching costs		Mixing costs		Switching costs		Mixing costs	
Task	Long	Short	Long	Short	Long	Short	Long	Short
Color-shape: SC long	—							
Color-shape: SC short	−.154	—						
Color-shape: MC long	*−.305*	*.031*	—					
Color-shape: MC short	*.041*	*−.230*	**.830***	—				
Language: SC long	.129	−.035	.089	.158	—			
Language: SC short	−.057	.069	.141	.120	.083	—		
Language: MC long	−.094	−.013	**.376***	**.375***	*−.061*	*.055*	—	
Language: MC short	−.065	−.107	.253	**.347***	*.229*	*−.158*	**.797***	—
Average parent education	−.242	.320	−.297*	**−.377***	−.006	.191	−.046	−.069
CWIT color name	−.103	.005	.138	.153	.105	−.042	.195	.183
CWIT reading	−.172	.069	.100	.070	.079	−.045	−.005	−.017
CWIT inhibition	−.072	.055	.323*	.264	−.131	.080	.207	.116
CWIT inhibition/switching	.070	−.117	.274	**.402***	−.036	.139	.319*	.267
CWIT inhibition cost	−.019	.056	.269	.197	−.203	.111	.111	.021
CWIT inhibition/switching cost	.196	−.143	.144	.270	−.123	.173	.203	.165
CWIT switch cost	.149	−.178	−.061	.132	.103	.058	.108	.150
Trails A	−.049	.074	.259	.218	.033	.049	.022	.006
Trails B	−.025	.079	.152	.087	−.189	.021	.081	−.019
Trails B/A	.003	.049	−.109	−.170	−.167	−.011	−.065	−.122
MINT English	.027	−.015	−.061	.026	.051	.190	.162	.163

Note. Italicized are correlations that violate independence. SC = Switching costs; MC = Mixing costs; CWIT = Color Word Interference Test; MINT = Multilingual Naming Test.
* Correlation is significant at $p \le .006$ (FDR-corrected); bolded = correlation is significant at $p \le .003$ (Bonferroni-corrected).

Chapter 2. Study 2

Cognitive Control Regions are Recruited in Silent Reading of Mixed-language Paragraphs in Bilinguals

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Abstract

When switching languages, bilinguals recruit a 'language control network' that overlaps with brain regions known to support general cognitive control, but it is unclear whether these same regions are recruited in passive comprehension of language switches. Using fMRI with a blocked design, 24 Spanish-English bilinguals silently read 36 paragraphs in which the default language was Spanish or English, and that had either 1) no switches, 2) function word switches or 3) content word switches. Relative to no switches, function switches activated the right IFG, bilateral MFG, and left IPL/ SMG. In contrast, switching on content words produced limited neural switching costs, and language dominance effects were also small. Finally, neural switching costs in silent reading were correlated with switching costs in cued picture-naming. Seemingly passive reading comprehension involves brain regions known to support cognitive control in active switching during production, possibly reflecting the operation of a modality-general switch mechanism.

Keywords. bilingualism, language switching, fMRI, cognitive control, neural switch costs

Cognitive Control Regions are Recruited in Silent Reading of Mixed-language Paragraphs in Bilinguals

An important human ability known as *cognitive control* enables flexibly changing between tasks, maintenance of multiple concepts active simultaneously, and inhibition of irrelevant responses in the service of goal-directed behavior. A related form of control is exercised by bilinguals, who must be able to manage dual-language activation to enable switching between languages when needed, while also avoiding switching by mistake. In the spotlight of current research on bilingualism is the extent to which mechanisms responsible for selecting which language to speak overlap with non-linguistic cognitive control processes (Abutalebi et al., 2012; for reviews see Abutalebi & Green, 2008; Bialystok, Craik, & Luk, 2012; Declerck & Philipp, 2015). Consistent with the possibility of shared mechanisms are studies in which bilinguals outperformed monolinguals in nonlinguistic task-switching (Prior & MacWhinney, 2010; Prior & Gollan, 2011; Stasenko, Matt, & Gollan, 2017), and inhibitory control (Bialystok, 2011; but see Hilchey & Klein, 2011; Paap et al., 2017). Further support for a cognitive control advantage for bilinguals are findings that lifelong bilingualism is associated with a delayed onset of cognitive decline due to Alzheimer's disease (for review see Bak & Alladi, 2014; Guzmán-Vélez and Tranel, 2015). However, this proposal remains controversial, as others have suggested that bilingual advantages are difficult to replicate and are highly variable (Lehtonen et al., 2018; Paap, Johnson, & Sawi, 2015; Paap & Sawi, 2014).

Neuroimaging studies also suggest overlap in mechanisms involved in language control and cognitive control (Abutalebi et al., 2012; Abutalebi & Green, 2007, 2008; Blanco-Elorrieta & Pylkkänen, 2016; de Baene, Duyck, Brass, & Carreiras, 2015; Garbin et al., 2010; Ma et al., 2014; Wang et al., 2007; Wang, Kuhl, Chen, and Dong, 2009). For instance, bilinguals activated regions of the brain hypothesized to support language control during nonlinguistic task switching (Branzi, Della Rosa, Canini, Costa, & Abutalebi; 2016; de Baene et al., 2015; Garbin et al., 2010), and switch trials in linguistic and nonlinguistic tasks elicited considerable overlap in activated brain regions, suggesting a shared "switch mechanism" (Weissberger et al., 2015). Abutalebi and Green (2007; 2008; 2016; see also Green &

Abutalebi, 2013) defined a “Language Control Network” which includes the dorsal anterior cingulate cortex (dACC), left caudate nucleus (CN), supramarginal gyrus (SMG), dorsolateral prefrontal cortex (dlPFC), and inferior frontal gyrus (IFG), regions also recruited for nonlinguistic control tasks (for a meta-analysis of fMRI studies of language switching see Luk et al., 2011).

A surprising gap in research on bilingual language switching is that the vast majority of studies focused on switches in speech production—even though language switches must be both produced and comprehended. Presumably, people spend more time comprehending than producing language and thus, the extent to which bilingualism entails an exercise in cognitive control might be much broader if the same cognitive control regions that support switching in production also support comprehension. A widely cited model of bilingual language processing assumes that similar brain mechanisms support production and comprehension of switches (e.g., van Heuven & Dijkstra, 2010; Grainger, Midgley, & Holcomb, 2010). While behavioral switching costs (i.e., the increase in reaction time when bilinguals need to switch languages compared to when they use the same language as the previous response) are less robust in comprehension than production (Declerck, Koch, Duñabeitia, Grainger, & Stephan, 2019; Declerck & Philipp, 2015), event-related potential (ERP) studies found that switches elicited an increased N400 component in sentence comprehension (e.g., Jackson et al., 2004; Moreno et al., 2002; Proverbio et al., 2004;). Switching may require more cognitive control in production than comprehension, because only in production do bilinguals need to choose between translation-equivalent alternatives, suppressing dual-language activation, whereas in comprehension whatever meanings and representations become active can remain active so long as they fit the intended meaning, without requiring inhibition.

The debate on whether language switches elicit processing costs in comprehension has been extended to neuroimaging studies; and here too, the findings are mixed. Abutalebi et al., (2007) reported significant activation in the caudate and the ACC for auditory perception of language switches, in particular for switching into the less-exposed language. They interpreted this pattern of activation as a switch cost at the neural level, similar to what is reported in production. One MEG study directly compared language switches in both production and comprehension, and to a nonlinguistic switching task, and found that switches in speech activated the DLPFC, a region that was also active in nonlinguistic switching, whereas switches in comprehension instead activated the left ACC, a region not associated with nonlinguistic switching in this study (Blanco-Elorrieta & Pylkkänen, 2016). In a follow-up study, *both* the DLPFC and ACC were implicated for language switches in comprehension, but no costs were found in these regions when switches were supported by more ecologically valid context (described in detail in the Discussion; Blanco-Elorietta & Pylkkänen, 2017). Finally, Hut, Helenius, Leminen, Mäkelä, and Lehtonen (2017) used MEG to examine trilingual language switching in auditory comprehension in early Finnish-Swedish bilinguals who learned English later in life. In this study, switching from English to either of the two native languages elicited a neural cost in the superior temporal gyrus (a region identified in the meta-analysis by Luk et al., 2011), but switching between the two native languages elicited no switch cost.

Given relatively few and mixed findings, it remains an open question if bilinguals rely on cognitive control regions when comprehending mixed-language speech. The majority of studies to date have focused on out-of-context speech in behavioral and neuroimaging studies, often requiring an explicit decision task such as semantic categorization, which likely misses critical aspects of bilingual language control as it occurs in more naturalistic use. Discrepant findings between ERP and behavioral studies could arise if behavioral measures are not as sensitive.

To that end, we used functional MRI to elucidate the neural regions involved in switching during silent reading by presenting full paragraphs written mostly in one language but with a handful of language switches, using a blocked design. We hypothesized that if switching during silent reading recruits the same language control network as observed in production, the same regions observed during production (e.g., DLPFC, ACC/SMA, IFG, caudate, SMG) will be recruited during switching in silent reading (as compared to non-switching). In previous work, when bilinguals read aloud mixed-language paragraphs, they produced intrusion errors (i.e., failures to switch) mostly on language-switched *function* words, and relatively infrequently on switched content word targets—a highly robust part-of-speech effect (Gollan & Goldrick, 2016; 2018; Gollan, Schotter, Gomez, Murillo, & Rayner, 2014;). These results suggest that, at least under some circumstances, controlling or monitoring selection of function words is more demanding for cognitive control mechanisms. As such, we hypothesize that conditions with function words (vs. content) switches should elicit more activation when compared against no switch conditions. However, because the requirement to produce switches is removed in silent reading, language control demands may change. For instance, it is possible that we would observe more robust neural costs for content than function words, since content words are prominent when prioritizing meaning during reading comprehension and are less likely to be skipped. Further, a prominent theory posits that unbalanced bilinguals use inhibition to switch between their languages, possibly inhibiting the dominant language to a greater degree (Inhibitory Control Model; Green, 1998). If inhibitory control also supports language switching in comprehension (e.g., Hut et al., 2017), we could observe greater activation of control regions for silent reading of paragraphs written primarily in the non-dominant language, i.e., *Spanish-default* paragraphs that required switching into English than vice versa. Finally, to provide further evidence on the nature of control mechanisms recruited during silent reading, after the scanning session we tested participants on two production-based language switching tasks (reading aloud of mixed-language paragraphs, picture naming with cued language switches), and examined correlations between neural costs of switching in silent reading and behavioral measures of switching in speech.

Methods

Participants

Participants were 24 right-handed (18 female) English-dominant Spanish-English bilinguals between 18 to 27 years of age, who were primarily undergraduates at the University of California, San Diego (UCSD) and participated for monetary compensation and/or course credit. Bilinguals acquired both languages by age 7, and were classified as English dominant using a picture naming test (the Multilingual Naming Test; MINT; Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2012); on average picture-naming test (MINT) scores were 13 (*SD* = 3; range = 5-17) points higher in English than in Spanish. Bilinguals were recruited from previous experiments that did not involve language switching or reading aloud. The minimum Spanish MINT score was 43/68. These strict selection criteria were applied to ensure inclusion of a relatively homogenous group of bilinguals who were proficient in both languages but also English dominant. See Table 2.1 for more details about the participants' language background and demographic characteristics. Participants were excluded for a history of significant head trauma, other neurologic or major psychiatric disorders, alcohol or substance abuse, current pregnancy, and metal objects in the body due to MRI specifications.

Materials and Procedure

fMRI paragraph reading task

A native Spanish-English bilingual research assistant adapted 36 paragraphs from published English-Spanish translations of short stories (modified from previous studies; Gollan & Goldrick, 2016; 2018; Gollan et al., 2014) that ranged from 100-120 words (M=108, SD=4.8) to ensure that an entire paragraph could be projected onto a screen at the foot of the scanner bed. A second native Spanish-English bilingual research assistant checked for errors and confirmed the intended manipulations. The design consisted of a 2 (language) by 3 (condition) structure in which each paragraph was written either primarily in English, or *English-default*, or primarily in Spanish, or *Spanish-default*, and either had no language switches, *single-language*, or had switches on *function* words or switches on *content* words. Thus each of the 36 paragraphs was modified so it could be presented in all 6 of the different conditions between subjects. An example paragraph and its condition-specific adaptations are presented in the Appendix. There were 12 language switches in each paragraph (i.e., 6 *switch-out of default* and 6 *switch-back to default* points), which were distributed evenly throughout the paragraph. Switch word manipulations were designed to be as natural as possible (though single word switches on function word targets do not conform to habitual constraints on spontaneously occurring switches, but are frequent targets of unintended language switches or *intrusion* errors; Muysken, 2000; Poulisse & Bongaerts, 1994). None of the switch words were cognates (i.e., translation equivalents that overlap in orthography and phonology such as *lemon* and *limón*), proper names, or long words (i.e., words ranged from 1-12 letters) and the same switch word did not appear more than twice in a given paragraph.

Paragraphs were presented in one of six different fixed-order lists; each bilingual was presented with one of these lists. For each list, participants completed 6 consecutive runs of six paragraphs (i.e., blocks; 36 total), with one paragraph per condition in each run (thus each bilingual saw a paragraph in each of the 6 conditions before reading a second paragraph in any of the 6 conditions). In each of the six lists, each paragraph was presented just once. Because the lists were designed for 24 subjects, across all lists, a given paragraph appeared a) four times in each of the six paragraph conditions, b) six times in each of the four run numbers, and c) six times in each of the four within-run positions.

fMRI paragraph reading task procedure

Two practice mixed-language paragraphs were completed prior to the scan to familiarize the participant with the task. During the scan, participants were asked to read the paragraph silently, without moving their head or lips, at a comfortable pace and to press a button when finished reading each paragraph (pilot data indicated that 30 seconds was sufficient to complete reading most if not all paragraphs for most bilinguals). Paragraphs were presented in a fixed-block design with 6 functional runs, where each run consisted of 6 blocks (i.e., 6 paragraphs), which represented all critical conditions. In each run, a fixation cross (15 s) preceded the presentation of each paragraph (30 s), and each run ended with a final fixation cross (15s), for a total time of 4 minutes and 45 seconds (see Figure 2.1).

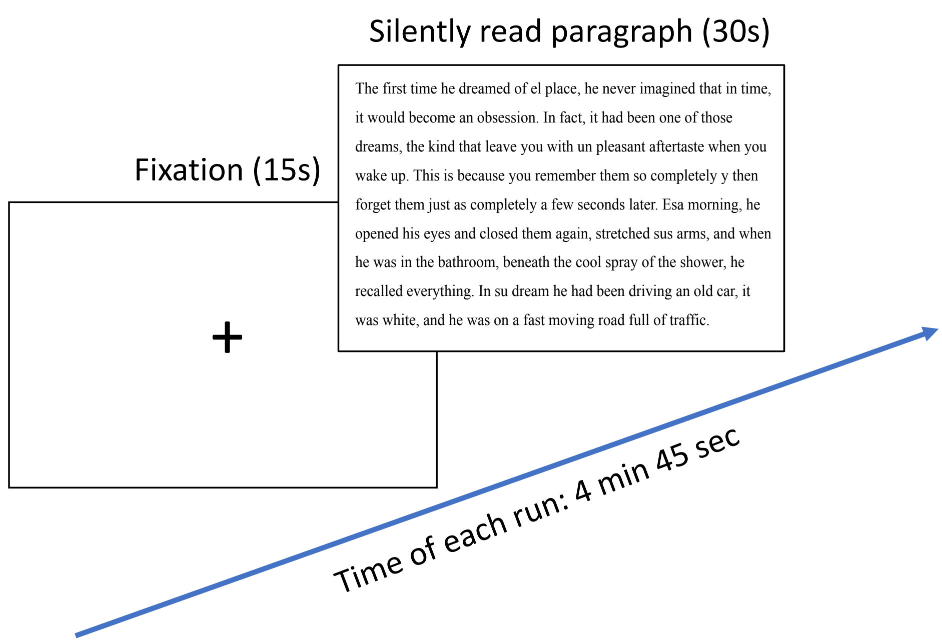

Figure 2.1. *Order of Events and Example Paragraph Stimuli Used in the fMRI task*

Stimuli were presented via an LCD projector on a screen at the end of the scanner bed, and were viewed through a mirror mounted on the head cage. A fiber-optic button box designed for use in the magnet recorded button presses. Stimuli were presented with a MacBook Pro laptop using PsychoPy v1.81.

Post-scan behavioral tasks

Paragraph reading aloud. After the scan, participants *read aloud* an additional set of paragraphs to provide a measure of individual differences in *production* of intrusion errors, to examine associations with comprehension of similar switches in the neural data. For the read-aloud task, six paragraphs were selected from news articles (i.e., excerpts from New York Times, CNN, and Huffington Post) that had a mean length of 205 words (*SD* = 7.3). Half of the paragraphs were English-default and half were Spanish-default. Paragraphs were modified to contain 12 switch words on *function words* (i.e., 24 switches in total when counting switches out and switches back to the default language). The focus on function words for the read aloud task was because content word switches elicited very few intrusion errors in previous studies (e.g., Gollan et al., 2014; Gollan & Goldrick, 2018). Six different fixed lists were created and counterbalanced and rotated across 24 participants using a Latin Square design. Across all participants, each paragraph was in the first, middle and last position equally often; and every default language was presented as first or second. See example of an English-default and a Spanish-default read-aloud paragraph in Appendix B.

Language switching in single picture naming. To obtain an additional measure of language switching ability in production, participants completed a picture naming task with cued language switches adapted from a previous study (see Kleinman & Gollan, 2016; Experiment 1a for full materials and details; the pseudo-voluntary "bottom-up" block was excluded).[9] Participants named 9 black-and-white line drawings of pictures in either English or Spanish based on a visual cue (i.e., a Mexican or a U.S.

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[9] Due to an experimental error, two participants completed the (i.e., voluntary) switching block as well.

flag). Bilinguals completed cued switching blocks (consisting of nonswitch or *stay* trials, and language *switch* trials), and English-only and Spanish-only blocks (*single*-language trials), in fully counterbalanced order. There were 108 critical trials in each block. Each trial began with a fixation cross (presented for 350ms) followed by a 150 ms blank screen. A language cue appeared on the screen above the center of the fixation. After 250 ms, the target picture appeared in the center of the screen while the cue remained on the screen. The cue and target remained on the screen until a response, or for a maximum of 3,000ms. An 850 ms inter-trial interval preceded the next trial.

fMRI Specifications and Analysis

Scanning parameters

Participants were scanned on a 3.0 Tesla General Electric (GE) Discovery MR750 whole body imager with an 8-channel head coil. Head movement was constrained with padding and taped to secure head position. A localizer scan was acquired initially to allow selection of the block of slices to be acquired during functional scanning and to assure good head placement in the scanner. Functional BOLD was obtained with a 1-shot gradient echo EPI scan. 22 cm FOV, 64 x 64 matrix, 3.0 mm x 3.0 mm in-plane resolution, TR= 2500 msec, TE= 30 msec, flip angle=90 degrees. Forty-four 3 mm thick sagittal slices covering the whole brain were acquired. Two field maps were collected to correct for distortions in EPI images due to susceptibility artifact. Structural MRI sequence included a high resolution T1-weighted Fast Spoiled Gradient Recall (3D FSPGR) scan to provide anatomic reference. 172 1 mm contiguous sagittal slices, FOV = 25.6 cm, TR = 8 ms, TE = 3.1ms, flip angle = 8, T1 = 600, 256 x 192 matrix, Bandwidth = 31.25 kHZ, frequency direction = S-I, NEX =1, scan time = 8 min 28 sec.

Data Processing and Analysis

fMRI data were analyzed and overlaid onto structural images with the Analysis of Functional Neuroimaging (AFNI) software package from the NIH (Cox, 1996). To minimize the effects of head motion, each individual's functional time series was corrected for motion using a three-dimensional iterated, linearized, weighted least-squares method with Fourier interpolation, and time-points with uncorrected motion outliers were excluded from statistical analysis. Slice timing correction was applied and runs were de-trended of low frequency signal drifts. A general linear model (GLM) approach was used on each participant's time-series to model the hemodynamic response (HDR) associated with every condition using AFNI's TENT function in 3dDeconvolve. The following predictors were used in the model. a constant, a linear trend, three parameters indicating the degree of motion correction performed in three rotational angles, and 6 stimulus vectors indicating the onset of each individual experimental condition (English default, Spanish default, English default with function switches, English default with content switches, Spanish default with function switches, and Spanish default with content switches). The '-gltsym' command of the TENT function was used to model combined conditions (English default with function switches + Spanish default with function switches; English default with content switches + Spanish default with content switches; English default + Spanish default). An estimated best-fit 7-lag impulse response was used which allowed the hemodynamic response to return to baseline. The modeled hemodynamic responses were subsequently scaled so that beta weights would be equivalent to percent signal change (PSC). Data were smoothed to 6 mm FWHM using AFNI's 3dBlurToFWHM. Registration to the MNI-152 atlas was performed using FMRIB's Non-linear Image Registration Tool (FNIRT), part of FSL (http://fsl.fmrib.ox.ac.uk/fsl/), and were resampled at a 3mm^3 resolution.

Within-group comparisons for each main contrast of interest—1) Function-word Switches vs Single-Language, 2) Content-word Switches vs Single Language, 3) Function-word Switches vs. Content-word Switches, 4) Spanish-default Switches vs. English-default Switches, 5) Spanish-default Function Switches vs. English-default Function Switches and 6) Spanish-default Content Switches vs. English-default Content Switches, were conducted using voxel-wise paired samples *t*-tests with percent signal change as the dependent variable (using AFNI's 3dttest++). Analyses were restricted to a small number of *a priori* regions of interest (ROIs), as per the recommendation to improve power and reduce an inflated false discovery rate. Five bilateral ROIs associated with cognitive and language control were selected based on prior findings (Abutalebi & Green, 2008; Luk et al., 2011) and included the middle frontal gyrus (MFG; i.e., dorsolateral prefrontal cortex; dlPFC), dorsal anterior cingulate cortex (dACC), inferior frontal gyrus (IFG; pars opercularis and triangularis), supramarginal gyrus (SMG), and the caudate nucleus (CN). ROIs were derived from the Harvard-Oxford atlas. Significance was determined by applying cluster-size correction derived from randomization of voxel-wise *t*-tests (via AFNI's Clustsim option in 3dttest++) and then feeding the randomized t-statistic maps onto Monte-Carlo simulations directly for cluster-size threshold determination (using AFNI's 3dClustSim) as per recommendation in response to reports of inflated false positive rate in fMRI group analysis tools (Eklund, Nichols, & Knutsson, 2016). To determine cluster significance for each ROI we used bi-sided significance testing, a per voxel threshold of $p < 0.01$, and a Bonferroni-corrected (for 5 ROIs) cluster-wise alpha threshold of $p < 0.01$ (results meeting a cluster-wise $p < 0.05$ threshold were reported, and especially for contrasts with halved power—i.e., contrasts 5 and 6 above—are highlighted in Table 2.2 and interpreted with caution). At the ROI level, the required minimum cluster size was 459 mm^3 (17 contiguous voxels) for the MFG, 486 mm^3 (18 contiguous voxels) for the dorsal ACC, 648 mm^3 (24 contiguous voxels) for the IFG, 540 mm^3 (20 contiguous voxels) for the SMG and 135 mm^3 (5 contiguous voxels) for the caudate.

Behavioral Data Analysis

For the post-scan paragraph reading aloud task, a native Spanish-English bilingual research assistant transcribed and classified errors as intrusions ($n = 231$; e.g., saying "la" instead of "the"), and partial intrusions ($n = 61$; e.g., starting to produce an intrusion but self-correcting before producing the error). The sum of intrusions and partial intrusions produced by each participant, separated by default language, was used for brain-behavioral correlations reported below.

For the post-fMRI language switching picture naming task, incorrect responses and RTs that were 2.5 standard deviations above or below each participant's mean RT were excluded from analyses. Mean reaction time (RT) for single, stay, and switch trials were calculated. To examine the associations between the neural cost of switching in reading and the behavioral cost of switching in production, switch costs (RT of switch trials – RT stay trials in mixed blocks) and mixing costs (RT of stay trials in mixed blocks – RT of single trials in single blocks) were calculated to be used as difference scores in the correlations reported below.

Brain-behavior Correlations

Percent signal change was extracted from each significant cluster reported in Table 2.2 (i.e., for function-word switches only) for each individual and condition. Difference scores representing the neural cost of switching were calculated by subtracting the mean percent signal change observed for single-language paragraphs from the mean percent signal change observed for paragraphs with function-word switches for each participant. These values were then correlated with behavioral data using Pearson bivariate correlations. Given the exploratory nature of correlations between neural and behavioral data, we focus on correlations that survived a false discovery rate (FDR) for multiple comparisons using the Benjamini-Hochberg procedure (Thissen, Steinberg, & Kuang, 2002; Williams, Jones & Tukey, 1999). A cut-off of $p = .029$ was determined by arranging p-values from lowest and highest and choosing the largest p-value that was smaller than the Benjamini-Hochberg critical value as threshold (accepting a FDR of 15%).

Results

fMRI Results

Our main questions of interest included. 1) Does silent reading of paragraphs with language switches incur a neural switching cost in the same language control regions as observed in studies of overt language switching (in production)? 2) Does recruitment of language control areas in silent reading differ by part of speech—i.e., content versus function switch words? and 3) Does language control differ for reading Spanish-default versus English-default paragraphs? We combined conditions to maximize power for these 3 main contrasts of interest, such that two conditions were always compared to two conditions in the voxel-wise student t-tests (with 12 paragraphs in each condition). To illustrate, to compute the neural cost associated with function word switching, two conditions were combined to create the overall switching condition (English-default function switches and Spanish-default function switches) and were tested against the combination of two single language conditions (i.e., English-only and Spanish-only paragraphs). Cluster location with coordinates and corresponding Z-values are shown in Table 2.2.

1) Function-word Switches vs. Single-Language

ROI analyses revealed four significant clusters in the Function-word Switches versus Single-Language contrast; bilinguals showed increased activation when silently reading paragraphs with switches on function words compared to single-language paragraphs without switches in the right IFG, left SMG, and the right and left MFG—or the DLPFC (cluster C1 to C4; see Table 2.2 and Figure 2.2).

2) Content-word Switches vs. Single-Language

In contrast to function-word switches, which revealed a number of significant results, when comparing Content-word Switches to Single-Language paragraphs, no clusters survived the most stringent correction. Only one cluster was significant using a cluster threshold of $p < 0.05$; this was in the left IFG (Table 2.2 and Figure 2.3).

3) Function-word Switches vs. Content-word Switches

Analysis 1 revealed many significant results, whereas Analysis 2 did not, implying a greater neural cost for silent reading of function versus content switches. However, when directly comparing paragraphs with switches on different parts of speech, there were no significant clusters in the same ROIs examined above. As explained above, this analysis collapsed across default-language (to maximize power); a different result emerged in follow-up comparisons presented below.

4) Spanish-default Switches vs. English-default Switches

No significant clusters were identified for switching in Spanish-default paragraphs versus in English-default paragraphs, collapsing across part of speech.

5) Function-word switches in Spanish-default vs. English-default

Increased activation was observed for reading Spanish-default with English function word switches, compared to English-default with Spanish function word switches in the right SMG (Table 2.2; Figure 2.4; this was significant only without the Bonferroni correction, at $p < 0.05$ cluster threshold level).

6) Content word switches in Spanish-default vs. English-default

No significant clusters (even with a $p < 0.05$ cluster threshold) were identified for switching in Spanish-default with English content word switches, compared to English-default with Spanish content word switches.

Spanish-only vs. English only

Having found some possibly significant differences between switches to Spanish versus English (for function word switches), an important control comparison is needed to determine if the increased activation in the right SMG may simply be an artifact of task difficulty (i.e., if rather than reflecting switching per se, this result reflects reading paragraphs written primarily in Spanish, the non-dominant language for these bilinguals, thus requiring greater recruitment of control regions). To consider this possibility, we compared Spanish-only paragraphs to English-only paragraphs using the more lenient cluster threshold ($p < 0.05$). No clusters emerged in the right SMG, the region of greatest interest given significant activation for function switches in Spanish-default versus English-default above. Similarly, no clusters emerged in the other four ROIs for this contrast. This suggests that observed activation for switching into English versus switching into Spanish cannot be solely explained by difficulty level.

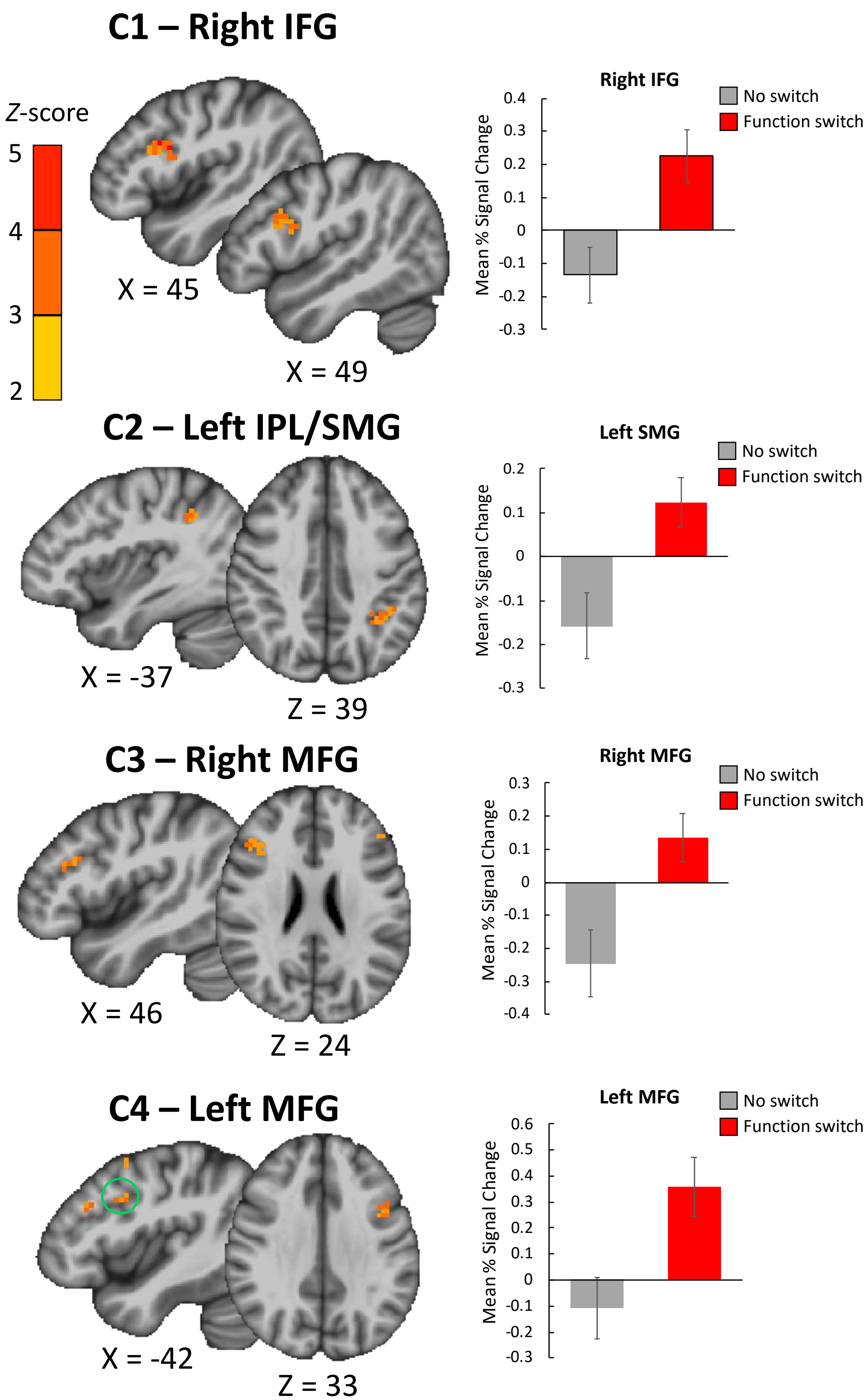

Figure 2.2. *Clusters showing significantly greater activation for reading paragraphs requiring switching languages on function words vs. single-language paragraphs in the right IFG (C1), left SMG (C2) and bilateral MFG—or the DLPFC region (C3 and C4). Note.* When there are multiple clusters depicted, a green circle represents the significant cluster. Error bars represent the standard error of the mean percent signal change.

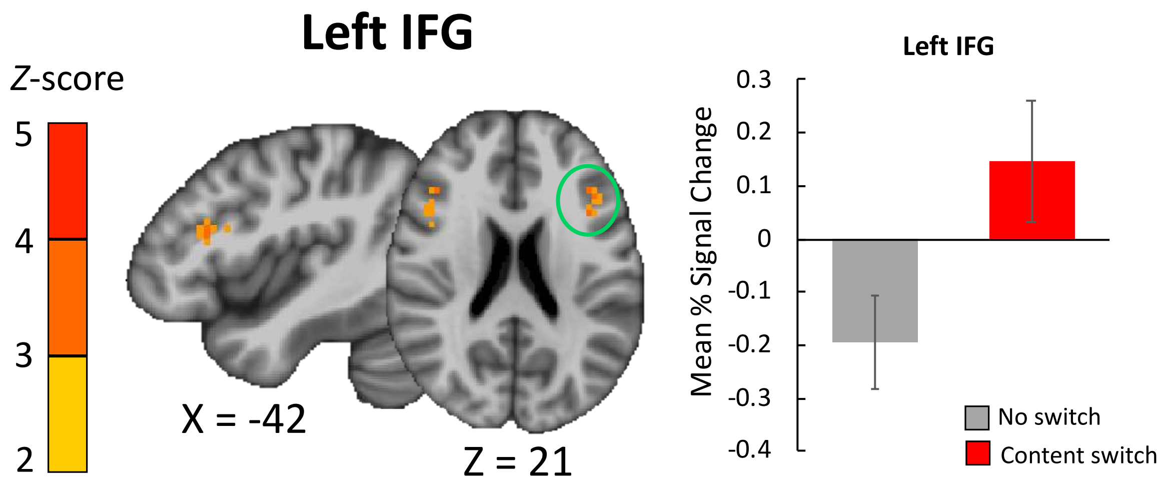

Figure 2.3. *Cluster in the left IFG showing significantly greater activation for reading paragraphs requiring switching languages on content words vs. single-language paragraphs. Note.* The green circle represents the significant cluster. Error bars represent the standard error of the mean percent signal change.

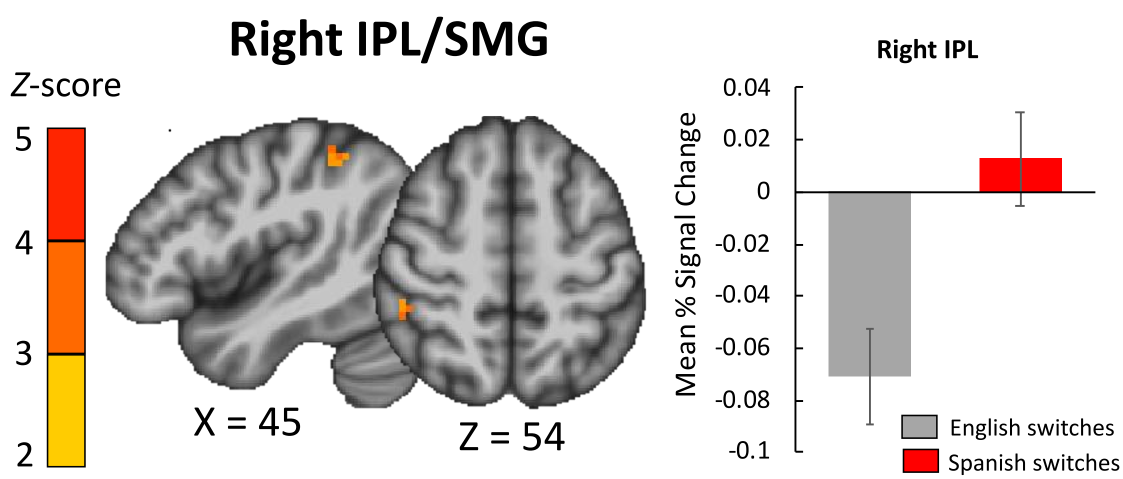

Figure 2.4. *Cluster in the right SMG showing significantly greater activation for reading Spanish-default paragraphs with function switches vs English-default paragraphs with function switches. Note.* Error bars represent the standard error of the mean percent signal change.

Behavioral Results

Silent paragraph reading RTs during fMRI scan

Mean RTs for each condition, and mean RT costs for reading paragraphs with switches versus single-language paragraphs are reported in Table 2.3. On some trials participants did not press the button to indicate they had finished reading the paragraph within the allotted time (i.e., 30 seconds; *M*= 14% of trials, SD = 11%). Of note, one participant's time-outs were approximately 3 standard deviations above the mean. When this participant was excluded from the analyses reported below, the pattern of activation remained the same. Trials with no responses were coded as the maximum of 30 seconds for the analysis reported below. Of the overall time-outs, 27% were from the Spanish-only condition, 31% from Spanish-default with function switches and 33% from the Spanish-default with content switches. In contrast, only 10% of all timeouts occurred on all English-default paragraphs collapsed (including switch and non-switch paragraphs).

A repeated-measures two-way ANOVA with default-language (English, Spanish) and condition (single, function switch, content switch) revealed main effects of default-language, such that bilinguals read English paragraphs faster than Spanish paragraphs ($F(1, 23) = 120.4$; $MSE = 803.8$; $p < 0.001$; $\eta^2 = 0.8$) and condition, such that bilinguals read single-language paragraphs faster than mixed-language paragraphs ($F(1, 23) = 14.3$; $MSE = 15.2$; $p < 0.001$; $\eta^2 = 0.4$). These main effects were qualified by a significant interaction between default-language and condition ($F(1, 23) = 8.5$; $MSE = 7.7$; $p = .001$; $\eta^2 = 0.3$). Follow-up comparisons revealed that in English-default paragraphs, there were significant RT differences between all pairwise conditions; bilinguals read single-language paragraphs slower than paragraphs with content switches, and read paragraphs with function switch slower than those with content switches (ps ≤ 0.04). In contrast, within Spanish-default paragraphs, bilinguals read single-language paragraphs faster than with content switches, but differences between single-language paragraphs and function-word switches, and between function and content word switch paragraphs were not significant (ps = .31 and .24, respectively). When log-transforming reaction times, the main effects and interaction remained unchanged. The difference in sensitivity between English and Spanish-default paragraphs to the switching manipulation could have been magnified by the large number of time-outs in the Spanish-default conditions.

Paragraph reading aloud post-fMRI

Table 2.4a reports number of intrusion errors bilinguals produced in the read-aloud task separated by each language and switch-out versus switch-back points, and Table 2.4b reports RTs for each type of paragraph. Bilinguals produced more intrusion errors ($t(23) = 4.1$; $p < 0.001$), and also read more slowly ($t(23) = 12.2$; $p < 0.001$) Spanish-default than English-default paragraphs, in line with previous findings (Gollan et al., 2014; Gollan & Goldrick, 2018). To maximize power, we collapsed switch-out and switch-back points, and included partial intrusions, when correlating intrusions with neural data[10].

Production of language-switches in single picture naming post-fMRI

One bilingual did not complete the picture-naming task. Table 2.5 reports mean RTs (5a) and error rates (5b) for each trial type, separated by language, as well as difference scores (switch and mixing costs). Table 2.5c reports mean intrusion errors produced (i.e., naming the picture correctly but not in the language that matched the cue) separated by language of the trial. Bilinguals produced a similar number of intrusions on cued Spanish versus cued English naming trials ($t < 1$), and a low number of intrusions; thus we collapsed across language for this variable in the correlations.

Switch costs. RTs for condition means were entered into a two-way repeated measures analysis of variance (ANOVA) with language of trial (English, Spanish) and trial type (stay, switch), as repeated measures factors. Participants exhibited significant switch costs, i.e., a main effect of trial type, $F(1,22) = 45.4$, $MSE = 109{,}415.7$; $p < 0.001$; $\eta^2 = 0.7$, and responded significantly slower on English trials, a reversed language dominance effect ($F(1,22) = 22.0$, $MSE = 54{,}683.7$; $p < 0.001$; $\eta^2 = 0.5$). Switch costs were similarly sized in English and Spanish; the interaction between language and trial type was not significant ($F < 1$; $p = .59$). The same ANOVA, but replacing RTs with error rates (in percentage) as the dependent variable, revealed only a main effect of trial type, such that there were significant switch costs in error rates, ($F(1,22) = 8.7$, $MSE = 0.012$; $p < 0.01$; $\eta^2 = 0.3$).

Mixing costs. A two-way repeated measures ANOVA with language of trial (English, Spanish) and trial type (single, stay), as repeated measures factors to compare non-switch trials across single versus

[10] The observed patterns did not differ when including only intrusions produced on switch-out points.

mixed language testing blocks showed that bilinguals paid significant mixing costs, i.e., a main effect of trial type, $F(1,22) = 86.2$, $MSE = 353{,}776.9$; $p < 0.001$; $\eta^2 = 0.8$, and named pictures more slowly on English trials, a reversed dominance effect (F (1,22) = 5.7, $MSE = 18{,}687.3$; $p < 0.05$; $\eta^2 = 0.2$). These main effects were qualified by a significant interaction, such that the mixing costs were bigger in English than in Spanish trials—a mixing cost asymmetry (F (1,22) = 10.0, $MSE = 13{,}690.7$; $p < 0.01$; $\eta^2 = 0.3$). Another ANOVA with the same trial structure and error rates as the dependent measure revealed a main effect of trial type, such that bilinguals paid significant mixing costs in error rates (F (1,22) = 17.0, $MSE = 0.008$; $p < 0.01$; $\eta^2 = 0.4$), and mixing costs were greater in English than in Spanish (F (1,22) = 7.7, $MSE = 0.002$; $p = 0.01$; $\eta^2 = 0.3$). The main effect of language was not significant in errors, (F (1,22) = 2.1, $MSE = 0.008$; $p = 0.17$; $\eta^2 = 0.3$).

Exploratory Correlations between fMRI BOLD Response during Silent Reading and Behavioral Language Switching

To further investigate relationships between cognitive and neural mechanisms underlying switching in silent reading and switching in speech production, we examined correlations, shown in Table 2.6, between neural costs of switching in silent reading (i.e., fMRI BOLD response) and switching and mixing costs in our picture-naming task, as well as intrusion errors produced in the read-aloud task. If a common language control mechanism serves both production and comprehension of switches, there should be correlations between neural switching costs in silent reading and measures of switching in speech production. Given the similarity between the two paragraph tasks, we anticipated a higher likelihood of finding correlations between neural data and the reading aloud task administered outside the scanner. Additionally, our blocked design did not allow us to distinguish switching from mixing costs in the neural data; however, correlations between neural data and switching versus mixing costs in the picture naming task could shed light on the cognitive mechanism underlying neural costs (e.g., neural costs measured during silent reading could be correlated with switching, mixing, or both costs, or none).

BOLD response for function switches

The neural costs of silent reading with function switches in the right IFG and in the right MFG were positively associated with switching costs in the picture naming task (*rs* = 0.43 and 0.46; *ps* = .03 for right IFG and right MFG, respectively). Separating switching costs in picture naming by language, the cost of switching into the dominant language (English) showed a robust correlation with the neural cost in the right IFG ($r = 0.59$; $p = .003$) and in the left SMG ($r = 0.48$; $p = 0.02$). A similar pattern was found in bilateral MFG, such that the neural costs of switching during reading were positively associated with English switch costs in production ($r= 0.47$; $p = 0.025$ and $r = 0.40$; $p = .06$ in left and right MFG, respectively), though these did not survive a more stringent FDR correction. Figure 2.5 illustrates the relationship between English switching costs in the picture naming task, and percent signal change in the significant activation clusters. In contrast, neural costs for function switches in these regions were not significantly correlated with the cost of switching into Spanish (the non-dominant language), or with mixing costs in either language (or overall, all *p*s ≥ 0.13). Additionally, contrary to our expectation of stronger associations between the two paragraph tasks, neural costs for function switches were not correlated with intrusion errors produced in the read-aloud task with switches on function words (all *r*s ≤ .24; *p*s ≥ .26; Table 2.6).

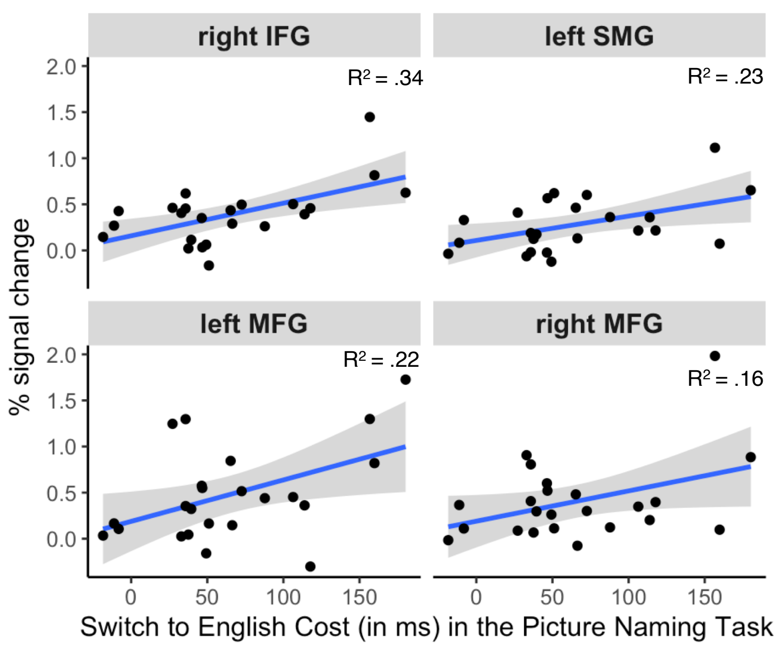

Figure 2.5. *Scatterplots of the correlations between switch costs in time in milliseconds (ms) in a picture naming task with cued language switches and neural switching costs with function word switches in the right IFG, left SMG, and bilateral MFG. Note*. The smoothing band represents 95% confidence intervals.

Interestingly, paragraph reading times in the read-aloud task were also not correlated with any neural costs for function switches (all rs < .29) neither for English-default nor for Spanish-default paragraphs (which all had function word switches). Furthermore, switch costs as calculated by behavioral RTs in the scanner were not significantly correlated with corresponding neural switch costs (all rs < .27).

Cross-task correlations between behavioral measures

Though intrusion errors were not significantly correlated with neural costs, this did not reflect a general failure of intrusions to correlate with any measure of language control. For example, the number of intrusions produced during reading aloud of English-default paragraphs (with switches into Spanish on function words) was significantly correlated with mixing costs for English picture naming trials ($r = 0.48$; $p = .02$). This trend was also observed in other mixing costs measures but did not reach significance (see Table 2.6). Finally, English-default intrusion errors exhibited a trend towards a correlation with English picture-naming switch costs ($p = .05$), which did not survive FDR correction. In summary, we did not observe many correlations between behavioral measures administered outside the scanner, but to the extent that we did these involved mixing (not switching) costs, thereby exhibiting a different pattern from the neural data, which tended to be correlated with switching (not mixing) costs.

Discussion

This study characterized the neural costs of language switching during silent reading of mixed-language paragraphs using functional MRI. Bilinguals silently read full paragraphs written in just one language, with a handful of switches on either function or content words with explicit instructions to avoid moving the head or mouth, and with no requirement to make decisions about content (only to press a button at completion). Our results revealed the neural costs of silently reading language switches to be similar to previous observations of switch costs in production of language switches (e.g., Ma et al, 2014; Wang et al., 2009; for review of this network see Abutalebi and Green, 2007; 2008; 2016; Green & Abutalebi, 2013; Luk et al., 2011). Specifically, function word switches elicited costs in the bilateral middle frontal gyrus (i.e., dorsolateral prefrontal cortex; dlPFC), right inferior frontal gyrus (RIFG), and left inferior parietal lobule/supramarginal gyrus (IPL/SMG; see Figure 2.2). By contrast, content word switches no elicited costs, or had a trend towards costs only in the left inferior frontal gyrus (LIFG; Figure 2.3) (i.e., without Bonferroni correction for multiple ROIs). Similar findings suggested that the neural cost of switching was greater for reading switches to English function words in Spanish-default paragraphs than for reading switches to Spanish function words in English-default paragraphs in the right IPL/SMG (Figure 2.4), resembling previous findings in production that switching into the dominant language was more costly. Finally, correlations with behavioral data revealed significant relationships between the neural cost of silently reading switches and switch costs found in production. Specifically, the neural cost of function word switches in the RIFG, left MFG, and left SMG was positively correlated with the behavioral cost of switching to the dominant language in cued picture naming Figure 2.5). These results support the notion of a modality-general switch mechanism that is used to process switches in both language comprehension and production, and is supported by the same (or similar) brain regions as nonlinguistic cognitive control.

Function Word Switches are More Costly

A priori, it was uncertain whether neural costs would be larger for function than content word switches, given that function words are often skipped entirely in reading (e.g., O'Regan, 1979; Saint-Aubin & Klein, 2001), and function word errors are difficult to detect even during explicit attempts at monitoring (Schotter et al., in press; Staub, Dodge & Cohen, 2018). Of greatest interest, function word switches elicited the most robust neural switch costs. This suggests a role of cognitive control for comprehension of language switches even when these occur on a minority of words in connected multi-sentence language processing, and for high frequency words that only provide grammatical information. Interestingly, although *unintended* switches most often involve function words (and interjections; both in spontaneous speech, Poulisse and Bongaerts, 1994; Poulisse, 1999, and in reading aloud; Gollan et al., 2014; Gollan & Goldrick, 2016; 2018), bilinguals do not typically switch on single function words intentionally (Muysken, 2000), thus making this manipulation less naturalistic (than content switches). Our finding of increased neural costs for function word switches in cognitive control regions is in line with findings by Abutalebi and colleagues (2007) who manipulated regularity of switches in an auditory perception task and found that switches that violate the well-formedness of the sentence structure activated the opercular portion of Broca's area and the left IPL, two of the same regions observed in our function switch contrast. In contrast, in that study well-formed switches activated inferior temporal regions related to lexical-semantic processing. Abutalebi and colleagues proposed that irregular switches may be first treated as grammatical violations, rather than lexical alternatives, because of their occurrence in unnatural positions. Thus, irregular switches may rely more on regions shown to support syntactic processes (i.e., pars opercularis and IPL; e.g., Caplan et al., 2000; Friederici, 2002 for review). Interestingly, in a MEG study, when the auditory comprehension task was made more naturalistic (i.e., participants listened to recording of spontaneous switching in bilingual conversations), activation in cognitive control areas (i.e., ACC and dlPFC) was not observed, and activation was only significant in the auditory cortex (Blanco-Elorrieta & Pylkkänen, 2017). Taken together, recruitment of cognitive control regions may be dependent on the nature of the task, with unnatural switches eliciting costs and more natural switches being 'cost-free' (although null findings must of course be interpreted with caution).

Cognitive Control Regions Recruited in Silent Reading of Language Switches

Our most robust cluster was observed in the right IFG, which has been implicated in domain-general inhibition of irrelevant manual or linguistic responses (e.g., in the Simon task in Jahfari et al., 2011; Aron et al., 2004b for review). For example, Aron and colleagues (2004a) compared patients with lesions to the right vs. the left IFG using a stop-signal task (which requires inhibition of a manual response) and found that patients with right (but not left) IFG lesions showed disrupted inhibition of responses, and damage to the right IFG positively correlated with the reaction time needed to inhibit the response. Further, in a language switching study Bruin and colleagues (2014) found significant neural switching costs in the right IFG (and the pre-SMA) for switching into second and third-learned languages, and significant correlations between BOLD response in the right IFG and pre-SMA and a behavioral measure of inhibition (Simon task interference effects in response times). Taken together, the common activation of the right IFG during language switching studies (de Bruin et al., 2014; Fu et al., 2017; the current study) and inhibition of manual responses (as observed in the stop-signal and Simon tasks; Aron et al., 2004a; 2004b; Jahfari et al., 2011) suggests that this region serves a domain-general role in response inhibition, including but not limited to language switching.

Our second largest cluster for switching was observed in the inferior parietal lobule (IPL), and specifically the supramarginal gyrus (SMG). This region was observed in one of the earliest language switching studies by Price, Green, and von Studnitz (1999) who used PET imaging to investigate translation or *reading* of visually presented words in German, English, or switching languages. They found that switching resulted in activation of the IFG and bilateral SMG. The SMG has been implicated in mapping orthography into phonology (e.g., Graves, Desai, Humphries, Seidenberg & Binder, 2010; for review Paz-Alonso, Oliver, Quiñones, & Carreiras, 2019) and the parietal cortex more generally has been shown to be important for letter identification and early stages of visual processing (Paz-Alonso et al., 2019). Thus it is possible that initial attempts to search for words in the wrong lexicon trigger grapheme to phoneme conversion to a greater extent on switch words, recruiting SMG. The posterior parietal cortex has also been implicated in general executive control and task-switching (e.g., Liston, Matalon, Hare, Davidson & Casey, 2006; see Ye & Zhou, 2009 for the role of the parietal lobe in resolving conflict in sentence comprehension). In line with the idea of a possible bilingual advantage in executive control, a structural neuroimaging study by Mechelli and colleagues (2004) found that bilinguals had increased gray matter volume in the left parietal lobe compared to monolinguals, with the greatest increase in volume present in early high-proficiency bilinguals. Finally, Abutalebi and Green (2008) conceptualize the posterior parietal cortex as biasing selection away from the language not in use or toward the language in use (see also Branzi et al., 2016 suggestion of IPL's role in engagement and disengagement of inhibitory control). Our finding of significant activation of the IPL suggests that similar processes may be involved during silent reading of switches—that is, the parietal cortex may be important for directing attentional resources to the target language.

Third, we found significant activation of the bilateral dlPFC for function word switches which replicates previous studies relating language-switching in production to the left (Hernandez et a., 2000; Rodriguez-Fornells et al., 2005; Wang et al., 2007) and the right dlPFC (Hernandez et al., 2001; Wang et al., 2007), with the hemispheric distinction and lateralization of the dlPFC's role in language switching as inconclusive. Bilateral dlPFC plays an important role in response selection and inhibition (Abutalebi & Green, 2007), as well as general attentional control (Aron et al., 2004a) and in particular in sustained top-down control (Braver, Reynolds, & Donaldson, 2003). The dlPFC was also implicated in both language switching and category switching (within a single language) in another study (de Baene et al., 2015) suggesting language control is a subdomain of general cognitive control (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Garbin et al., 2010; Abutalebi et al., 2012). Furthermore, our observation of the dlPFC is in line with a study of out-of-context switches in auditory comprehension (in a word picture matching task) in which left dlPFC activation was found when switches were cued (i.e., by pictures of bilingual or monolingual interlocutors or arbitrary colors; Blanco-Elorrieta & Pylkkänen, 2017).

We did not observe significant activation in two other predicted ROIs—the caudate and ACC. The dorsal ACC has been shown to support error detection, task monitoring, and conflict resolution (Aarts, Roelofs & van Turennout, 2008; Kerns et al., 2004). The caudate—a subcortical region traditionally associated with motor control and general cognitive control (Graybiel, 1997; 2000)—has been consistently implicated in language switching and inhibition (e.g., Crinion et al., 2006; Abutalebi & Green, 2008). Previously both the left caudate and the ACC were observed during auditory perception of switches in comprehension in one fMRI study (Abutalebi et al., 2007) and the ACC was implicated in switching in comprehension in two recent MEG studies in which stimuli were isolated words or numbers (Blanco-Elorrieta & Pylkkänen, 2016; 2017). It is possible that the ACC only weakly supports switches in comprehension, and therefore is observed in some studies but not others. However, null effects are difficult to interpret, and methodological differences between studies make direct comparison difficult (e.g., our study involved silent reading whereas others involved auditory comprehension tasks). Setting aside possible debate over which exact regions are implicated, taken together, our findings do at least suggest an important role of the prefrontal and parietal regions in switching in comprehension in the visual domain, possibly supporting a modality-general switch mechanism for these regions.

Inhibition? Switching into the Dominant versus the Non-dominant Language

Language dominance effects are robust in bilingual research—bilinguals generally respond faster when naming pictures in their more dominant (i.e., more proficient) compared to non-dominant language under a single language context (e.g, Gollan, Kleinman & Wierenga, 2014; Ivanova & Costa, 2008). However this pattern reverses in blocks that require language switching—that is, switching into the dominant language is usually more costly than when switching into the non-dominant language, or sometimes language dominance even reverses entirely in mixed-language blocks (e.g., Christoffels et al., 2007; Declerck, Phillipp, & Koch, 2013; Gollan & Ferrerira; 2009; Meuter & Allport, 1999; for review see Kleinman & Gollan, 2018). These findings are often attributed to inhibitory control (e.g., Green, 1998)—that is, to produce words in the non-dominant language, the more dominant language must be inhibited, so that when returning to the dominant language, bilinguals must overcome inhibition, leading to large switch costs (Meuter & Allport, 1999; for review see Declerck & Philipp, 2015). In the current study, language dominance effects were found only in one cluster in the right IPL/SMG (and only without the most stringent correction) when bilinguals read paragraphs written mostly in Spanish with some switches to English on function words (relative to English-default paragraphs with switches to Spanish on function words). This result mirrors published behavioral data—in a read aloud task, bilinguals produced the most intrusion errors on non-dominant default paragraphs with switches into the dominant language (e.g., Fadlon et al., in press; Gollan et al., 2014; Gollan & Goldrick, 2016; 2018; Gollan, Stasenko, Li & Salmon, 2017; Li & Gollan, 2018; Schotter et al., in press). Similarly, in behavioral tasks administered after the fMRI task in the current study, bilinguals exhibited larger switch costs when switching to English than Spanish in picture-naming (see Table 2.5), and produced the most intrusions in Spanish-default paragraphs in the read-aloud task (see Table 2.4a). However, note that button press responses for in-scanner paragraph reading times exhibited the opposite pattern, a result we speculate may reflect lack of sensitivity/ceiling effect due to reading times in Spanish being close to our 30-second cutoff.[11] Further, the effects we observed in the right IPL/SMG could not be attributed simply to the difficulty associated with completing a task primarily in the non-dominant language rather than something related specifically to switching into a dominant language, given that we found no significant increase in activation in the SMG when comparing Spanish-only to English-only paragraphs.

A similar pattern was found in a neuroimaging study of comprehension. In an auditory semantic categorization task, Hut and colleagues (2017) found that switches from the later-learned English to either of the two native languages in trilinguals resulted in greater activation in the superior temporal gyrus, and this increase was not found for the reverse contrast (i.e. switching from either native language to English). Further, they found that English non-switch trials showed greater activation in the bilateral IFG (compared to non-switch trials in the native languages), and suggested this reflects inhibition of the native languages while using English, even in a receptive task. In a production study, Fu et al., 2017 found that switching into the dominant language elicited greater neural costs in the bilateral IFG, the right dlPFC and the SMA. Thus, while both Hut et al. and Fu et al. suggested their results reveal active suppression of the dominant (or native) language, different brain regions were implicated – and similar underlying mechanisms could be here, though more work is needed to determine which brain regions are involved. The notion of inhibition is highly debated (MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003; Rey-Mermet, Gade, & Oberauer, 2018), and while the observed activation in classic cognitive control regions could signify application of inhibition, it could instead indicate activation of stimulus-relevant information, or possibly both (e.g., Cohen, Dunbar, & McClelland, 1990; Egner & Hirsch, 2005; for review see Aron, 2007).

[11] This finding of less robust switch costs for switching into L1 as found in behavioral RTs (i.e., Table 2.5) patterns with previous behavioral studies that did not find a larger cost for switching into L1 than into L2 in comprehension (e.g., Bultena et al, 2015; Reynolds, Schlöffel, & Peressotti, 2016; but see Wang, 2015).

Clues into the Modality-Generality of the Switch Mechanism

The appearance of some control regions in a silent reading task that did not require overt responses, and which arguably could not have elicited response competition (at least not at the level of overtly planning responses)—provides additional constraints on how these effects should be interpreted. To examine the relationships between comprehension and production, we contrasted the neural costs observed in silent reading with post-scan behavioral measures of switching in production. The only production task that was significantly correlated with neural switching costs was the single picture-naming task—specifically switch costs in English—while the task that resembled our silent-reading during fMRI task far more, the paragraph read-aloud task, elicited no significant correlations with neural switching costs. It is unclear why the behavioral task most similar to the fMRI task did not reveal any significant correlations. However, it is not simply the case that intrusions were insufficiently sensitive to switching ability because we found correlations between intrusions in English-default paragraphs and mixing costs for English in the picture naming task. Because we found switching cost correlations consistently for multiple brain regions, this suggests that neural costs found when contrasting single versus mixed language paragraphs reflects operation of a *switching* mechanism, whereas intrusion errors and mixing costs may measure more sustained forms of control. This pattern appears in line with a production study by Wang and colleagues (2009) who found that sustained language control (defined by mixing costs) versus transient control (defined by switching costs) elicited differential activation patterns. That is, the left inferior parietal lobule was more specific to transient control (and is similar to the robust correlation between behavioral and neural costs in the IPL in the current study), whereas the left MFG was activated for both switching and mixing costs. This interpretation, though speculative, implies the existence of a modality-general switch mechanism that supports processing of language switches in both comprehension and production, and switching in general (both linguistic and nonlinguistic, because of the brain regions involved.

It is reasonable to ask if our scanner task exclusively measured processes associated with reading comprehension processes or if bilinguals may have been covertly *producing* speech (even though they were instructed to read silently), thus resulting in activation in regions often observed in switching during production. Some aspects of our data seem inconsistent with this interpretation. First, correlations between neural switch cost data and intrusion errors produced in the reading-aloud task administered after the scan (which was very close in design to the task in the scanner) were null. Second, silent reading sometimes involves auditory imagery or a “voice in the head” (Huey, 1908), suggesting that visual word recognition requires processes similar to “sounding out” words —i.e., *phonological recoding* (e.g., Frost, 1998). Although many reject strong notions of phonological recoding in reading, it is generally agreed that sound-based representations are computed during reading (Rastle & Brysbaert, 2006 for review). These processes are more likely when reading is less proficient and automatic, and reading of orthographically transparent languages such as Spanish. Thus, for our bilinguals Spanish was both less proficient and more transparent, and as such, reading Spanish versus English covertly should also have activated regions known to support phonological recoding (e.g., left posterior fusiform gyrus; see Dietz, Jones, Gareau, Zeffiro, & Eden, 2005). However, this region was not observed in an exploratory whole brain analysis; using an uncorrected p of .001; see Table 7), which showed higher activation for Spanish-only than English-only paragraphs in the right precentral gyrus and in the left thalamus; no significant activation was observed in the reverse direction. Our finding of the precentral gyrus is in line with a meta-analysis by Liu and Cao (2016) who reported that precentral gyri (and bilateral superior/middle temporal gyri) were recruited to a greater degree when bilinguals read in a second language (L2) that was more transparent than the first language (L1). Finally, the few studies that contrasted silent and overt reading suggested that reading aloud elicits more robust activation of the phonological processing system (Barch et al., 1999; Huang, Carr, Cao, 2002), particularly bilateral pre-motor and motor, auditory, and extra-striate regions (Dietz et al., 2005). Similarly, Berken et al. 2015 demonstrated that *sequential* bilinguals, who in some ways more closely resemble bilinguals in our study, activated speech-motor control areas (e.g., left IFG, left premotor cortex, and left fusiform gyrus) more strongly than simultaneous bilinguals when reading aloud in L2 compared to L1. Because the majority of the above regions were not implicated in the present study, with the exception of the right precentral gyrus (i.e., primary motor cortex) and the left IFG (though a weak effect), it appears less likely that the correlations we observed across modalities reflected covert motoric output or increased phonological decoding involved in switching.

Although we cannot definitively rule out the possibility that covert reading or perhaps more likely, automatic phonological recoding during silent reading, played some role in recruiting control regions normally associated with switching in production, what we can say with confidence is that these regions are recruited even when bilinguals do not need to select a single response for production. That is, in our study during the scan bilinguals did not speak, did not move their mouths, and did not need to make any explicit classification of which language they were reading or any other type of decision that might have recruited frontal regions of the brain that support response selection. The significant recruitment of cognitive control regions even in a silent reading task with only 6 switch words per paragraph, and on high frequency function words that are often skipped in reading is surprising and suggests that silent reading should perhaps not be viewed as relatively passive. Instead bilinguals maintain active expectations about language membership of upcoming words, and recruit frontoparietal control regions to resolve conflict between these expectations and violation thereof when reading switch words. Although prediction in language comprehension is not a novel concept, the *mechanism* of prediction is controversial (e.g., Kuperberg & Jaeger, 2015). For instance, it is possible that language membership may be accomplished by a 'prediction-by-production' mechanism as proposed in some comprehension accounts (e.g., Dell & Chang, 2014; Pickering & Gambi, 2018), whereby the reader may retrieve covert production representations (i.e., covert imitation) to predict an upcoming switch, with the aid of context and association.

Limitations and Future Directions

A notable limitation of the current study is a relatively small sample size, which leaves uncertain how null effects should be interpreted (e.g., lack of significant activation of the ACC). Further, we have assumed throughout that activation of regions previously reported for production of switches (in other studies) in comprehension of switches (in the present study) supports the notion that language switches are processed by at least partially overlapping underlying cognitive mechanisms whether they occur in comprehension or production. By extension, because language switches activated cognitive control regions that were also recruited to support non-linguistic cognitive control processes in bilinguals and monolinguals alike, an even more general purpose switching mechanism might also be supported. However, caution is warranted in interpreting our results to reflect non-linguistic control and requires more explicit confirmation. Fedorenko, Behr, and Kanwisher (2011) cautioned against such interpretations; using fMRI to functionally define classic language regions on an *individual* subject level, they examined responses in these regions to nonlinguistic (e.g., general working memory, general cognitive control) functions and found little to no overlap between linguistic and non-linguistic functions (with the exception of the left MFG and verbal working memory). Their analysis suggests a high degree of functional specificity within the same brain regions for supporting language versus nonlinguistic functions (for review see Fedorenko, 2014). Thus, additional work with better targeted analyses and that includes both linguistic and non-linguistic tasks will be needed to test if what seems to be shared regions might instead involve functional separation at the level of individual rather than group-based contrasts.

Conclusions

Our finding of neural costs observed for silent reading of function switches, and the correlations between switching costs across fMRI and behavioral tasks, are consistent with proposals that bilinguals rely on shared control mechanisms when producing and comprehending language switches (e.g., van Heuven & Dijkstra, 2010; Grainger et al., 2010). Although open to interpretation and in need of further confirmation, even if control mechanisms are only partly shared across modalities (comprehension and production) and across domains (linguistic and nonlinguistic), bilinguals may be exercising cognitive control regions in the brain more frequently than assumed (if counting only overt production of switches). If so, a greater implication would be that bilingualism constitutes a more intensive mental gym for cognitive control regions. Broadly, this could be relevant for understanding cognitive reserve (Bialystok, Abutalebi, Bak, Burke, & Kroll, 2016; Perani & Abutalebi, 2015), if bilingualism also entails a greater need for cognitive control than monolingualism (an assertion that is disputed; Lehtonen et al., 2018; Paap et al, 2017; Antón, Carreiras & Duñabeitia, 2019; Antón, Fernández-García, Carreiras, Duñabeitia, 2016).

Setting this debate aside, while silent reading seems to be a relatively passive task, only a handful of language switches on function words distributed across processing of an entire paragraph was sufficient to elicit significant activation of cognitive control regions of the brain. The possibility of processing mechanisms that supports conflict resolution in both language comprehension and production has broad implications for understanding language processing in bilinguals and monolinguals alike.

Tables

Table 2.1. *Participant Demographics and Bilingual Language Background Characteristics*

Participant Characteristic	*M*	*SD*
Age	20.0	2.5
Years of education	13.3	1.6
% female	75	--
% right-handed	100	--
% Hispanic	96	--
Age of first exposure to English (years)	4.1	1.7
Age of first exposure to Spanish (years)	0.2	0.4
% English daily use currently	81.8	11.5
% English daily use when growing up	58.5	10.9
Self-rated English speaking proficiency[a]	6.8	0.5
Self-rated English reading proficiency[a]	6.7	0.7
Self-rated English writing proficiency[a]	6.5	0.7
Self-rated English listening proficiency[a]	6.9	0.4
Self-rated Spanish speaking proficiency[a]	6.3	0.7
Self-rated Spanish reading proficiency[a]	6.3	0.7
Self-rated Spanish writing proficiency[a]	5.8	1.0
Self-rated Spanish listening proficiency[a]	6.8	0.4
Average caregiver education (years)	11.5	3.9
Average years lived abroad	2.0	2.9
Average English (dominant) MINT[b]	61.8	2.7
Average Spanish (non-dominant) MINT[b]	48.9	3.9
Average MINT difference[b]	12.9	3.3

[a] Self-ratings are based on a 7-point scale. 1 = almost none; 2 = very poor; 3 = fair; 4 = functional; 5 = good; 6 = very good; 7 = like a native speaker
[b] Maximum score is 68 points

Table 2.2. *Brain Regions Showing Significantly Higher BOLD Response in Regions of Interest*

Contrast and Cluster Number	Hemi-sphere	Anatomical region	BA/ Subregion	Cluster volume (mm^3)	CM MNI coordinates (x, y, z)*	*Z*-value at peak intensity	Effect size (r)	Mean PSC	95% CI
1) Function-word Switches vs. Single Language									
C1	R	Inferior Frontal Gyrus	BA 44;45	1,188	46.1, 12.9, 24.3	4.3	0.73	0.36	[0.23, 0.50]
C2	L	Inferior Parietal Lobule (Supramarginal Gyrus)	BA 40	675	-36.8, -46.6, 39.5	3.4	0.70	0.28	[0.17, 0.39]
C3	R	Middle Frontal Gyrus	BA 46;9	621	41.1, 26.2, 23.8	3.5	0.66	0.38	[0.22, 0.58]
C4	L	Middle Frontal Gyrus	BA 46;9	486	-44.0, 9.3, 34.3	3.3	0.59	0.47	[0.27, 0.67]
*2) Content-word Switches vs. Single Language***									
	L	Inferior Frontal Gyrus	BA 44;45	405	-40.9, 25.2, 18.1	3.5	0.62	0.34	[0.17, 0.52]
*3) Spanish-default Function Switches vs. English-default Function Switches***									
	R	Inferior Parietal Lobule (Supramarginal Gyrus)	BA 40	378	45.5, -40.5, 51.5	3.3	0.65	0.08	[0.05, 0.12]

Note. The contrasts refer to 1) reading paragraphs with function switches compared to no switches, 2) reading paragraphs with content switches compared to no switches, and 3) reading paragraphs primarily written in Spanish with English function switches compared to paragraphs primarily in English with Spanish function switches. PSC = percent signal change; 95% confidence intervals (CI) from 1000 bootstrapping samples using a paired-sample *t*-test.

* Coordinates reflect center of mass (CM) of resulting cluster.

** Clusters for these two contrasts did not survive a more stringent correction for multiple comparisons (i.e., these results are presented at a corrected cluster-wise threshold of $p < .05$ rather than .01; see Methods) and should be interpreted with caution.

Table 2.3. *Means and Standard Deviations (SD) of Total Paragraph Reading Times (RT) in Seconds, for each Condition of Interest in the fMRI Task*

	Paragraph word-order			
	English-default		Spanish-default	
Paragraph Type	*M*	*SD*	*M*	*SD*
Single Language	20.0	3.8	25.5	2.9
Content Switches	21.3	3.4	26.1	2.7
Function Switches	21.8	3.4	25.7	2.7
Content Switch cost	1.3	1.5	0.6	1.3
Function Switch cost	1.8	1.8	0.2	1.1

Note. Also shown are RT costs associated with reading while switching languages versus reading in a single language.

Table 2.4.

(a) *Means, Standard Deviations (SD), and Minimum and Maximum Number of Intrusion and Partial Intrusion Errors Produced in the Read-aloud Task*

Language	*Error*	*Switch-out*				*Switch-back*			
Spanish-default		*M*	*SD*	Min	Max	*M*	*SD*	Min	Max
	Intrusions	5.4	4.0	1	16	1.1	1.4	0	5
	Partial intrusions	0.4	0.6	0	2	1.1	1.2	0	4
English-default									
	Intrusions	2.7	1.7	0	6	0.6	0.8	0	2
	Partial intrusions	0.2	0.4	0	1	0.8	0.8	0	3

(b) *Means and Standard Deviations (SD) for Reaction Times in the Read-aloud Task*

Paragraph Type	*M*	*SD*
Spanish-default with English switches	100.2	20.8
English-default with Spanish switches	73.6	12.8

Table 2.5. *Means and Standard Deviations for (a) Reaction Time (ms) and (b) Error Rates (%)*

(a)

	Language			
	English		Spanish	
Trial Type	*M*	*SD*	*M*	*SD*
Single	679	80	674	63
Stay	827	117	774	96
Switch	892	133	847	137
Mixing cost	148	80	100	68
Switch cost	65	53	73	67

(b)

	Language			
	English		Spanish	
Trial Type	*M*	*SD*	*M*	*SD*
Single	0.01	0.02	0.03	0.06
Stay	0.03	0.04	0.04	0.07
Switch	0.06	0.06	0.06	0.08
Mixing cost	0.03	0.03	0.01	0.02
Switch cost	0.03	0.05	0.02	0.05

(c)

Language of trial	*M*	*SD*	Min	Max
Spanish	1.9	3.4	0	16
English	2.1	1.9	0	9

Note. Table 2.5c additionally shows minimum and maximum by participant number of picture naming trials produced in the wrong language (i.e., failing to match the cue).

Table 2.6. *Associations between fMRI Data and Behavioral Measures of Language Switching*

	Right MFG	Left MFG	Right IFG	Left SMG	English SC[a]	Spanish SC[a]	English MC[b]	Spanish MC[b]	Picture-naming Intrusions[c]	Read-aloud intrusions Eng. default[d]	Read-aloud intrusions Span. default[d]
Right MFG	–										
Left MFG	0.446*	–									
Right IFG	0.727**	0.554**	–								
Left SMG	0.485*	0.495*	0.394	–							
English SC[a]	0.400	**0.466***	**0.586****	**0.478***	–						
Spanish SC[a]	0.328	0.173	0.164	0.089	0.313	–					
English MC[b]	−0.085	−0.260	−0.310	−0.229	0.011	0.497*	–				
Spanish MC[b]	0.002	0.100	−0.035	−0.052	0.320	0.517*	0.507*	–			
Picture-naming intrusions[c]	−0.190	−0.209	−0.386	0.240	0.054	0.028	0.060	0.030	–		
Read-aloud intrusions Eng. default[d]	−0.014	−0.081	0.005	0.210	0.414*	0.304	**0.484***	0.377	0.383	–	
Read-aloud intrusions Span. default[d]	−0.122	−0.189	−0.242	−0.120	0.136	0.287	0.297	0.405	.292[e]	0.611**	–

Note. Data represent percent signal change in significant clusters observed for function switches > single language; i.e., the neural cost of switching with function words. * $p < .05$; ** $< p = .01$; ^ $p = .05$. In bold are correlations that survive FDR correction ($p \leq .029$). In gray font are correlations that violate independence and/or within-task correlations that are not of interest.

[a] SC = switch cost in the picture-naming switching task (i.e., RT switch trials – RT stay trials)

[b] MC = mixing cost in the picture-naming switching task (i.e., RT stay trials – RT single trials)

[c] Picture-naming intrusions = incorrect language used on trials in the picture-naming task (e.g., saying *cat* instead of *gato* when cued to name a picture in Spanish)

[d] Sum of intrusions and partial intrusions made at all switch points in the read-aloud paragraphs task administered after the fMRI scan

[e] This correlation was 0.622 before an extreme outlier (5 standard deviations above the average amount of picture naming intrusions produced) was removed.

Table 2.7. *Brain Regions Showing Higher BOLD Response for Reading Single-Language Paragraphs Written in Spanish Compared to Single-Language Paragraphs Written in English*

Contrast and Cluster Number	Hemi-sphere	Anatomical region	BA/Subregion	Cluster volume (mm^3)	CM MNI coordinates (x, y, z)*	*Z*-value at peak intensity
Spanish Only vs. *English Only*						
C1	R	Precentral gyrus	BA 4	108	28.5, −13.5, 48	3.5
C2	L	Thalamus	–	54	1.4, −3, −6	3.7

Note. This is an exploratory whole-brain analysis (uncorrected voxel-wise *p* of .001).

Appendix

A. Example paragraph as it was modified to appear in each of 6 conditions (between participants). Underlines included only in this example for illustration (switches were not underlined in the version participants saw).

English Only. Throughout the Land of the Pig River, the name Mrs. Peace was very well known by almost everyone. It wasn't so much because of the gossip that traveled from village to village, but due to the many stories that circulated declaring her adventures and mischief. It is said that there was something magnetic and charming about her personality that attracted everyone's attention. In fact, there was always someone that had something very funny to say about Mrs. Peace. The curious thing is that very few people spoke negatively about her in spite of her eccentric behavior. The truth is that almost everyone admired her—even the youngest ones.

English default-function. Throughout the Land of the Pig River, el name Mrs. Peace was very well known by almost everyone. It wasn't so much because of the gossip que traveled from village to village, but due to the many stories that circulated declaring her adventures and mischief. It is said that there was something magnetic y charming about her personality that attracted everyone's attention. In fact, there was always someone that had algo very funny to say about Mrs. Peace. The curious thing is that very poca people spoke negatively about her in spite of her eccentric behavior. La truth is that almost everyone admired her—even the youngest ones.

English default-content. Throughout the Land of the Pig River, the nombre Mrs. Peace was very well known by almost everyone. It wasn't so much because of the chisme that traveled from village to village, but due to the many stories that circulated declaring her adventures and mischief. It is said that there was something magnetic and encantador about her personality that attracted everyone's attention. In fact, there was always someone that had something very chistoso to say about Mrs. Peace. The curious thing is that very few gente spoke negatively about her in spite of her eccentric behavior. The verdad is that almost everyone admired her—even the youngest ones.

Spanish Only. Por toda la Tierra del Río Puerco, el nombre doña Paz era muy bien conocido por casi todos. No era tanto por el chisme que corría de pueblo en pueblo, sino por las muchas historias que circulaban declarando sus aventuras y travesuras. Se dice que había algo magnético y encantador de su personalidad que llamaba la atención de todos. De hecho, siempre había alguien que tenía algo muy chistoso que decir de doña Paz. Lo curioso es que muy poca gente hablaba mal de ella a pesar de su comportamiento excéntrico. La verdad es que casi todos la admiraban—hasta los más jóvenes.

Spanish default-function. Por toda la Tierra del Río Puerco, the nombre doña Paz era muy bien conocido por casi todos. No era tanto por el chisme that corría de pueblo en pueblo, sino por las muchas historias que circulaban declarando sus aventuras y travesuras. Se dice que había algo magnético and encantador de su personalidad que llamaba la atención de todos. De hecho, siempre había alguien que tenía something muy chistoso que decir de doña Paz. Lo curioso es que muy few gente hablaba mal de ella a pesar de su comportamiento excéntrico. The verdad es que casi todos la admiraban—hasta los más jóvenes.

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B. Example of an English-default and a Spanish-default paragraph with switches on function words used in the post-scan reading aloud task. Underlines included only in this example for illustration (switches were not underlined in the version participants saw).

"Greenland is Melting Away". At last the helicopter took off the team's gear hanging from an attached net sling. Los scientists gazed at the seemingly endless surface of the ice, beneath the chopper, spreading in todo directions, threaded with blue rivers and lakes. After a forty minute flight, el pilot cautiously bounced the helicopter on the ice, making sure it was hard enough to land on.

Stepping out, the scientists were hit por the cold of the Greenland summer, the temperature ranged from 26 to 40 degrees mientras they were there, a constant wind and the glare of the sun.

As the researchers began to set up camp, Bob, un doctoral student from the University of Wyoming, headed toward the river, silent as it sliced through the ice. More than cualquier other member of the team, the success of the mission rested on sus shoulders.

Bob was 31 years old, and grew up kayaking and rafting in Oregon. He designed the complex rope and pulley system, modeled on swift-water boat rescue systems, qu would be crucial to gleaning data de the dangerous waters. Before coming to Greenland, he spent months refining y practicing his rope system on rivers in Wyoming.

"Este es el tiempo que tardas en sacar tu teléfono cuando estás solo". Si estás solo en una habitación, te tomará un promedio de 44 segundos sacar your teléfono del bolso y empezar a revisarlo, de acuerdo con un experimento hecho en Alemania and el Reina Unido.

The documento reveló que los hombres tardan sólo 21 segundos— menos de la mitad del lapso promedio— en tomar su teléfono, mientras that las mujeres esperan generalmente 57 segundos antes de hacerlo.

Durante el estudio los participantes fueron grabados by una cámara escondida para capturar "objetivamente" el contacto with su celular. El 73% de los participantes usaron sus celulares durante la sesión de espera que duró 10 minutos, y durante that periodo tanto hombres como mujeres lo usaron por 5 minutos.

Sin embargo, almost todos los participantes aseguraron haber pasado entre dos y tres minutos sin recurrir a su teléfono celular."La gente está más atada a estos dispositivos de lo que creen, sobre todo when están a solas," estimó Jens Bindert, académico of la Universidad en el Reino Unido. "La inmediatez de la información y las interacciones realizadas a través de our dispositivos móviles hacen que estos sean más than una pieza de tecnología, convirtiéndose en un compañero digital, así como en una conexión con el mundo exterior.

References

Aarts, E., Roelofs, A., & van Turennout, T. M. (2008). Anticipatory activity in anterior cingulate cortex can be independent of conflict and error likelihood. *Journal of Neuroscience, 28,* 4671–4678.

Abutalebi, J., Brambati, S. M., Annoni, J.-M., Moro, A., Cappa, S. F., & Perani, D. (2007). The neural cost of the auditory perception of language switches. an event-related functional magnetic resonance imaging study in bilinguals. *The Journal of Neuroscience, 27*, 13762–13769.

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S., & Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex, 22*, 2076–2086.

Abutalebi, J., & Green, D. (2007). Bilingual language production. The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*, 242-275.

Abutalebi, D. J., & Green, D. W. (2008). Control mechanisms in bilingual language production. Neural evidence from language switching studies. *Language and Cognitive Processes*, *23*, 557–582.

Abutalebi, J., & Green, D. W. (2016). Neuroimaging of language control in bilinguals. neural adaptation and reserve. *Bilingualism. Language and Cognition*, *19*, 689–698.

Antón, E., Carreiras, M., & Duñabeitia, J. A. (2019). The impact of bilingualism on executive functions and working memory in young adults. *PLOS ONE*, *14*.

Antón, E., Fernández García, Y., Carreiras, M., & Duñabeitia, J. A. (2016). Does bilingualism shape inhibitory control in the elderly? *Journal of Memory and Language*, *90*, 147–160.

Aron, A. R. (2007). The neural basis of inhibition in cognitive control. *The Neuroscientist. A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *13*, 214–228.

Aron, A., Monsell, S., Sahakian, B., & Robbins, T. (2004a). A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain, 127*, 1561-1573.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004b). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8*, 170–177.

Barch, D. M., Sabb, F. W., Carter, C. S., Braver, T. S., Noll, D. C., & Cohen, J. D. (1999). Overt verbal responding during fMRI scanning. empirical investigations of problems and potential solutions. *NeuroImage*, *10*, 642–657.

Berken, J.A., Gracco, V.L., Chen, J., Watkins, K.E., Baum, S., Callahan, M., & Klein, D. (2015). Neural activation in speech production and reading aloud in native and non-native languages. *NeuroImage, 112,* 208-217.

Bialystok, E. (2011). Reshaping the mind. The benefits of bilingualism. *Canadian Journal of Experimental Psychology*, *65*, 229–235.

Bialystok, E., Abutalebi, J., Bak, T. H., Burke, D. M., & Kroll, J. F. (2016). Aging in two languages. Implications for public health. *Ageing Research Reviews*, *27*, 56–60.

Bialystok, E., Craik, F. I. M., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control. evidence from the Simon task. *Psychology and Aging*, *19*, 290–303.

Bialystok, E., Craik, F. I. M., & Luk, G. (2012). Bilingualism. consequences for mind and brain. *Trends in Cognitive Sciences*, *16*, 240–250.

Blanco-Elorrieta, E., & Pylkkänen, L. (2016). Bilingual language control in perception versus action. MEG reveals comprehension control mechanisms in anterior cingulate cortex and domain-general control of production in dorsolateral prefrontal cortex. *Journal of Neuroscience*, *36*, 290–301.

Blanco-Elorrieta, E., & Pylkkänen, L. (2017). Bilingual language switching in the laboratory versus in the wild. the spatiotemporal dynamics of adaptive language control. *The Journal of Neuroscience, 37*, 9022–9036.

Branzi, F. M., Della Rosa, P. A., Canini, M., Costa, A., & Abutalebi, J. (2016). Language control in bilinguals. Monitoring and response selection. *Cerebral* Cortex, *26*, 2367-2380.

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron*, *39*, 713–726.

Bultena, S., Dijkstra, T., & Hell, J. G. V. (2015). Language switch costs in sentence comprehension depend on language dominance. Evidence from self-paced reading. *Bilingualism. Language and Cognition*, *18*, 453–469.

Caplan, D., Alpert, N., Waters, G., & Olivieri, A. (2000). Activation of Broca's area by syntactic processing under conditions of concurrent articulation. *Human Brain Mapping*, *9*, 65–71.

Cohen, J. D., Dunbar, K., & McClelland. J. L. (1990). On the control of automatic processes. A parallel distributed processing account of the Stroop effect. *Psychological Review, 97,* 332-361.

Cox, R. W. (1996). AFNI. Software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research, 29*, 162-173.

Christoffels I. K., Firk C., Schiller N. O. (2007). Bilingual language control. an event-related brain potential study. *Brain Res, 1147*, 192–208.

Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., … Price, C. J. (2006). Language control in the bilingual brain. *Science, 312*, 1537–1540.

de Baene, W., Duyck, W., Brass, M., & Carreiras, M. (2015). Brain circuit for cognitive control is shared by task and language switching. *Journal of Cognitive Neuroscience*, *27*, 1752–1765.

de Bruin, A., Roelofs, A., Dijkstra, T., & FitzPatrick, I. (2014). Domain-general inhibition areas of the brain are involved in language switching. FMRI evidence from trilingual speakers. *NeuroImage*, *90*, 348–359.

Declerck, M., Koch, I., Duñabeitia, J. A., Grainger, J., & Stephan, D. N. (2019). What absent switch costs and mixing costs during bilingual language comprehension can tell us about language control. *Journal of Experimental Psychology. Human Perception and Performance*, *45*, 771–789.

Declerck, M., & Philipp, A. M. (2015). A review of control processes and their locus in language switching. *Psychonomic Bulletin & Review*, *22*, 1630–1645.

Declerck, M., Philipp, A. M., & Koch, I. (2013). Bilingual control. Sequential memory in language switching. *Journal of Experimental Psychology. Learning, Memory and Cognition*, 39, 1793–1806.

Dell, G. S., & Chang, F. (2013). The P-chain. relating sentence production and its disorders to comprehension and acquisition. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *369*.

Dietz, N. A. E., Jones, K. M., Gareau, L., Zeffiro, T. A., & Eden, G. F. (2005). Phonological decoding involves left posterior fusiform gyrus. *Human Brain Mapping*, *26*, 81–93.

Egner, T. & Hirsch, J. (2005). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience. 8*, 1784-1790.

Eklund A, Nichols T, Knutsson H. (2016). Cluster failure. Why fMRI inferences for spatial extent have inflated false-positive rates. *Proceedings of the National Academy of Sciences, 113*, 7900-5.

Fadlon J., Li C., Prior A., and Gollan T.H. (in press). Using what's there. Bilinguals adaptively rely on orthographic and color cues to achieve language control. *Cognition*.

Fedorenko, E. (2014). The role of domain-general cognitive control in language comprehension. *Frontiers in Psychology*, *5*.

Fedorenko, E., Behr, M. K., & Kanwisher, N. (2011). Functional specificity for high-level linguistic processing in the human brain. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 16428–16433.

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, *6*, 78–84.

Frost, R. (1998). Toward a strong phonological theory of visual word recognition. true issues and false trails. *Psychological Bulletin*, *123*, 71–99.

Fu, Y., Lu, D., Kang, C., Wu, J., Ma, F., Ding, G., & Guo, T. (2017). Neural correlates for naming disadvantage of the dominant language in bilingual word production. *Brain and Language*, *175*, 123–129.

Hernandez, M., Costa, A., & Avila, C. (2010). Bridging language and attention. brain basis of the impact of bilingualism on cognitive control. *NeuroImage*, *53*, 1272–1278.

Gollan, T. H., & Ferreira, V. S. (2009). Should I stay or should I switch? A cost-benefit analysis of voluntary language switching in young and aging bilinguals. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*, 640–665.

Gollan, T. H., & Goldrick, M. (2016). Grammatical constraints on language switching. Language control is not just executive control. *Journal of Memory and Language*, *90*, 177–199.

Gollan, T.H., & Goldrick, M. (2018). A switch is not a switch. Syntactically driven bilingual llanguage control. *Journal of Experimental Psychology. Learning, Memory, & Cognition.*

Gollan, T. H., Kleinman, D., & Wierenga, C. E. (2014). What's easier. Doing what you want, or being told what to do? Cued versus voluntary language and task switching. *Journal of Experimental Psychology. General*, 143, 2167-2195.

Gollan, T. H., Schotter, E. R., Gomez, J., Murillo, M., & Rayner, K. (2014). Multiple levels of bilingual language control. Evidence from language intrusions in reading aloud. *Psychological Science*, *25*, 585–595.

Gollan, T. H., Stasenko, A., Li, C., & Salmon, D. P. (2017). Bilingual language intrusions and other speech errors in Alzheimer's disease. *Brain and Cognition*, *118*, 27–44.

Gollan, T.H., Weissberger, G., Runnqvist, E., Montoya, R.I., & Cera, C.M. (2012). Self-ratings of spoken language dominance. A multi-lingual naming test (MINT) and preliminary norms for young and aging Spanish-English bilinguals. *Bilingualism. Language and Cognition, 15,* 594-615.

Grainger, J., Midgley, K., & Holcomb, P. J. (2010). Re-thinking the bilingual interactive- activation model from a developmental perspective (BIA-d). In M. Kail & M. Hickmann (Eds.), *Language acquisition across linguistic and cognitive systems* (pp. 267–284). New York. Benjamins.

Graves, W. W., Desai, R., Humphries, C., Seidenberg, M. S., & Binder, J. R. (2010). Neural systems for reading aloud. a multiparametric approach. *Cerebral Cortex, 20*, 1799–1815.

Graybiel, A. M. (1997). The basal ganglia and cognitive pattern generators. *Schizophrenia Bulletin*, *23*, 459–469.

Graybiel, A. M. (2000). The basal ganglia. *Current Biology*, *10*, R509–R511.

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism.Language and Cognition*, *1*, 67–81.

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals. The adaptive control hypothesis. *Journal of Cognitive Psychology, 25*, 515–530.

Hernandez, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish–English bilinguals. An fMRI study. *NeuroImage*, *14*, 510–520.

Hernandez, A. E., Martinez, A., & Kohnert, K. (2000). In search of the language switch. an FMRI study of picture naming in Spanish–English bilinguals. *Brain and Language*, *73*, 421–431.

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*, 625–658.

Huang, J., Carr, T. H., & Cao, Y. (2002). Comparing cortical activations for silent and overt speech using event-related fMRI. *Human Brain Mapping*, *15*, 39–53.

Hut, S. C. A., Helenius, P., Leminen, A., Mäkelä, J. P., & Lehtonen, M. (2017). Language control mechanisms differ for native languages. Neuromagnetic evidence from trilingual language switching. *Neuropsychologia*, *107*, 108–120.

Ivanova, I., & Costa, A. (2008). Does bilingualism hamper lexical access in speech production? *Acta Psychologica*, *127*, 277–288.

Jackson, G. M., Swainson, R., Cunnington, R., & Jackson, S. R. (2001). ERP correlates of executive control during repeated language switching. *Bilingualism. Language and Cognition*, *4*, 169–178.

Jahfari, S., Waldorp, L., Wildenberg, W. P. M. van den, Scholte, H. S., Ridderinkhof, K. R., & Forstmann, B. U. (2011). Effective connectivity reveals important roles for both the hyperdirect (fronto-subthalamic) and the indirect (fronto-striatal-pallidal) fronto-basal ganglia pathways during response inhibition. *Journal of Neuroscience*, *31*, 6891–6899.

Kerns, J. G., Cohen, J. D., Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*, 1023–1026.

Kleinman, D., & Gollan, T. H. (2016). Speaking two languages for the price of one. Bypassing language control mechanisms via accessibility-driven switches. *Psychological Science*, *27*, 700-714.

Kleinman, D., & Gollan, T. H. (2018). Inhibition accumulates over time at multiple processing levels in bilingual language control. *Cognition*, *173*, 115-132.

Kuperberg, G,R., & Jaeger, T.F. (2015). What do we mean by prediction in language comprehension? *Language, Cognition, and Neuroscience, 31*, 32-59.

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychological Bulletin*, *144*, 394–425.

Li, C., & Gollan, T. H. (2018). Cognates facilitate switches and then confusion. Contrasting effects of cascade versus feedback on language selection. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *44*, 974–991.

Liston, C., Matalon, S., Hare, T. A., Davidson, M. C., & Casey, B. J. (2006). Anterior cingulate and posterior parietal cortices are sensitive to dissociable forms of conflict in a task-switching paradigm. *Neuron*, *50*, 643–653.

Liu, H., & Cao, F. (2016). L1 and L2 processing in the bilingual brain. A meta-analysis of neuroimaging studies. *Brain and Language*, *159*, 60–73.

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2011). Cognitive control for language switching in bilinguals. A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes*, *27*, 1479–1488.

Ma, H., Hu, J., Xi, J., Shen, W., Ge, J., Geng, F., Wu, Y., Guo, J., & Yao, D. (2014). Bilingual cognitive control in language switching. An fMRI study of English-Chinese late bilinguals. *PLoS ONE*, *9*, 1-8.

MacLeod, C. M., Dodd, M. D., Sheard, E. D., Wilson, D. E., & Bibi, U. (2003). In Opposition to

Inhibition. In *Psychology of Learning and Motivation - Advances in Research and Theory* (Vol. 43, pp. 163-214).

Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., & Price, C. J. (2004). Neurolinguistics. structural plasticity in the bilingual brain. *Nature*, *431*, 757.

Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming. Asymmetrical costs of language selection. *Journal of Memory and Language*, *40*, 25–40.

Moreno, E. M., Federmeier, K. D., & Kutas, M. (2002). Switching languages, switching palabras (words). an electrophysiological study of code switching. *Brain and Language*, *80*, 188–207.

Muysken, P. (2000). Bilingual speech. A typology of code-switching. Oxford. Cambridge University Press.

O'Regan, K. (1979). Saccade size control in reading. Evidence for the linguistic control hypothesis. *Perception & Psychophysics*, *25*, 501–509.

Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex*, *69*, 265–278.

Paap, K. R., & Sawi, O. (2014). Bilingual advantages in executive functioning. problems in convergent validity, discriminant validity, and the identification of the theoretical constructs. *Frontiers in Psychology*, *5*, 1-15.

Paap, K.R., Myuz, H. Anders, R.T., Bockelman, M., Mikulinsky, R & Sawi, O.M. (2017). No compelling evidence for a bilingual advantage in switching or that frequent language switching reduces switch cost, *Journal of Cognitive Psychology, 29*, 89-112.

Paz-Alonso, P. M., Oliver, M., Quiñones, I., & Carreiras, M. (2019). Neural basis of monolingual and bilingual reading. *The Oxford Handbook of Neurolinguistics*.

Perani, D., & Abutalebi, J. (2015). Bilingualism, dementia, cognitive and neural reserve. *Current Opinion in Neurology*, *28*, 618–625.

Pickering, M. J. & Gambi, C. (2018). Predicting while comprehending language. A theory and review. *Psychological Bulletin, 144*, 1002-1044.

Poulisse, N. (1999). Slips of the tongue. Speech errors in first and second language production. Amsterdam/Philadelphia. John Benjamins.

Poulisse, N., & Bongaerts, T. (1994). First language use in second language production. *Applied Linguistics*, *15*, 36–57.

Price, C. J., Green, D. W., & von Studnitz, R. (1999). A functional imaging study of translation and language switching. *Brain*, *122*, 2221–2235.

Prior, A. & Gollan, T.H. (2011). Good language-switchers are good task-switchers. Evidence from Spanish-English and Mandarin-English bilinguals. *Journal of the International Neuropsychological Society. JINS*, *17*, 682–691.

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism. Language and Cognition*, *13*, 253–262.

Proverbio, A. M., Leoni, G., & Zani, A. (2004). Language switching mechanisms in simultaneous interpreters. an ERP study. *Neuropsychologia*, *42*, 1636–1656.

Rastle, K., & Brysbaert, M. (2006). Masked phonological priming effects in English. Are they real? Do they matter? *Cognitive Psychology*, *53*, 97–145.

Rey-Mermet, A., Gade, M., & Oberauer, K. (2018). Should we stop thinking about inhibition? Searching for individual and age differences in inhibition ability. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *44*, 501–526.

Reynolds, M. G., Schlöffel, S., & Peressotti, F. (2016). Asymmetric switch costs in numeral naming and number word reading. Implications for models of bilingual language production. *Frontiers in Psychology*, *6*, 1-15.

Rodriguez-Fornells, A., Balaguer, R. D. D., & Münte, T. F. (2006). Executive control in bilingual language processing. *Language Learning*, *56*, 133–190.

Saint-Aubin, J., & Klein, R. M. (2001). Influence of parafoveal processing on the missing-letter effect. *Journal of Experimental Psychology. Human Perception and Performance*, *27*, 318–334.

Schotter, E.R., Li, C., & Gollan, T.H. (in press). What reading aloud reveals about speaking. Regressive saccades implicate a failure to monitor, not inattention, in the prevalence of intrusion errors on function words. *Quarterly Journal of Experimental Psychology.*

Stasenko, A., Matt, G., & Gollan, T. H. (2017). A relative bilingual advantage in switching with preparation. Nuanced explorations of the proposed association between bilingualism and task switching. *Journal of Experimental Psychology. General, 146,* 1527-1550.

Staub, A., Dodge, S., & Cohen, A. L. (2019). Failure to detect function word repetitions and omissions in reading. Are eye movements to blame? *Psychonomic Bulletin & Review*, *26*, 340–346.

Thissen, D., Steinberg, L., & Kuang, D. (2002). Quick and easy implementation of the Benjamini-Hochberg procedure for controlling the false positive rate in multiple comparisons. *Journal of Educational and Behavioral Statistics*, *27*, 77–83.

van Heuven, W. J. B., & Dijkstra, T. (2010). Language comprehension in the bilingual brain. fMRI and ERP support for psycholinguistic models. *Brain Research Reviews*, *64*, 104–122.

Wang, X. (2015). Language control in bilingual language comprehension. evidence from the maze task. *Frontiers in Psychology*, *6*, 1-12.

Wang, Y., Kuhl, P. K., Chen, C., & Dong, Q. (2009). Sustained and transient language control in the bilingual brain. *NeuroImage*, *47*, 414–422.

Wang, Y., Xue, G., Chen, C., Xue, F., & Dong, Q. (2007). Neural bases of asymmetric language switching in second-language learners. An ER-fMRI study. *NeuroImage*, *35*, 862–870.

Weissberger, G. H., Gollan, T. H., Bondi, M. W., Clark, L. R., & Wierenga, C. E. (2015). Language and task switching in the bilingual brain. Bilinguals are staying, not switching, experts. *Neuropsychologia*, *66*, 193–203.

Williams, V. S. L., Jones, L. V., & Tukey, J. W. (1999). Controlling error in multiple comparisons, with examples from state-to-state differences in educational achievement. *Journal of Educational and Behavioral Statistics*, *24*, 42–69.

Ye, Z., & Zhou, X. (2009). Conflict control during sentence comprehension. fMRI evidence. *NeuroImage*, *48*, 280–290.

Author's Note

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Chapter 3. Study 3

Failure to Reverse Language Dominance in Aging Bilinguals.

Evidence for the Inhibitory Deficit Hypothesis

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Abstract

Inhibitory control is thought to play a key role in how bilinguals switch languages and may also decline in aging. We tested this hypothesis by examining if older bilinguals exhibited reversed language dominance effects, a signature of global inhibition of the dominant language that leads bilinguals to name pictures more slowly in the dominant than the nondominant language in mixed-language testing blocks. Twenty-five older and 48 younger Spanish-English bilinguals completed a cued language switching task. To test if inhibition is applied at the whole-language or lexical level, we first presented one set of pictures repeatedly, then introduced a second list halfway through the experiment. Younger but not older bilinguals exhibited reversed language dominance. In younger bilinguals, dominance reversal transferred to, and was even larger in, the second list (compared to the first). These results support the hypotheses that aging impairs proactive control and that bilinguals rely on inhibition of the dominant language to switch languages. This further suggests that inhibition is applied primarily at the whole-language level, but may be partially offset by repetition interacting with more automatic lexical-level control in ways that are not yet fully understood.

Keywords. bilingualism, aging, language switching, proactive control, reversed language dominance

Failure to Reverse Language Dominance in Aging Bilinguals.

Evidence for the Inhibitory Deficit Hypothesis

The concept of inhibition is used in many different ways across psychology and the cognitive sciences with considerable disagreement as to what inhibition is and how it can best be measured. In neuroscience, inhibition refers to the nervous system—unequivocally, neurons have either excitatory or inhibitory functions. Cognitive inhibition usually refers to the ability to suppress or ignore irrelevant information in the service of achieving current goals (inhibiting a motor response, resisting the urge to have a donut or another slice of pizza; attempting to focus on the task at hand rather than the noise outside, etc.).

According to a popular theory of cognitive aging, cognitive inhibition decreases as we age—that is, older adults are more likely to be distracted by external and internal stimuli than younger adults, which could be associated with aging-related changes in the frontal lobes (Raz et al., 2005; Tamnes et al., 2013; Zanto & Gazzaley, 2019 for review). The proposal that aging leads to decline in the ability to suppress dominant responses and ignore irrelevant information is called the 'Inhibitory Deficit Hypothesis', henceforth *IDH* (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999; Zacks & Hasher, 1994). The IDH has been used to explain aging-related changes in various cognitive domains (e.g., working memory/attention, episodic memory, language comprehension, and spatial and reasoning abilities; see Hasher, 2015 for updated theory). Some of the most compelling evidence for the IDH came from negative priming studies, in which younger but not older participants exhibited slowed or less accurate responses to a target item that previously needed to be ignored/inhibited (i.e., a nontarget distractor item on a previous trial). The absence of negative priming implied a failure to inhibit distractors in older adults (e.g., Kane et al., 1997; but see Sullivan and Faust, 1993).

However, studies designed to test broad definitions of the IDH have been mixed, which may reflect a lack of consistency in methodology including use of different tasks, different ways of controlling for slowing in aging, as well as non-uniform participant samples (e.g., some older adults may have had mild cognitive impairment). To attempt to resolve this issue with a meta-analytic approach and using

Bayesian hypothesis testing for null effects, Rey-Mermet & Gade (2018) evaluated the hypothesis of an inhibition deficit in aging by examining tasks proposed to tap three types of inhibition—1) ignoring distracting information (flanker test, N-2 repetition costs); 2) suppressing a dominant response (go/no-go or stop-signal tasks); and 3) ignoring response interference (Stroop task, Simon task). They found that older adults showed impaired inhibition on only two tasks (the go/no-go and stop-signal tasks), whereas other tasks showed either no aging deficit (several versions of the Stroop task, flanker task and n-2 repetition costs) or inconclusive evidence requiring future research (Simon task and positive and negative compatibility tasks).

Reactive Versus Proactive Control

In attempt to specify under which conditions aging-related declines might be observed, recent empirical evidence has suggested a dual mechanism model of cognitive control (Braver, 2012; Braver, Gray, & Burgess, 2007)—*reactive* (also termed transient) and *proactive* (also termed sustained). Reactive control is defined as stimulus-driven attention recruited on the fly to resolve interference once it is detected, whereas proactive control refers to the ability to sustain information in working memory and prepare for potential interference (prior to its occurrence). Proactive control is thought to be slow-acting and effortful (e.g., Posner & Snyder, 1975) whereas reactive control is fast-acting and automatic (e.g., Jacoby, Lindsay, Hessels, 2003). Aging studies suggest that the most reliable age-related declines are observed in proactive control (e.g., Braver et al., 2001; 2005; see Wasylyshyn, Verhaeghen, & Sliwinski, 2011 for meta-analysis related to task switching costs) with relatively spared reactive control (Braver et al., 2007; Bugg, 2014; Kray & Lindenburger, 2000; Meiran et al., 2001). These findings imply that a working memory and monitoring limitation in normal aging may explain many age-related declines observed on measures of inhibition and task-switching, whereas selective attention – which requires reactive control – is believed to be largely intact across the lifespan. Other domain-general cognitive theories posit that many declines in healthy aging are a byproduct of general decline in sensory and perceptual processes (e.g., slowed processing speed, reduced visual acuity and hearing), offering a noninhibitory explanation of many aging deficits (e.g., Burke & Osborne, 2007; MacLeod et al., 2003; Salthouse, 2010; Verhaeghen, 2011).

Inhibition in Language Processing: the Bilingual Lens

In the domain of language production, the IDH has been criticized for failing to support existing empirical evidence (e.g., Taylor and Burke, 2002; Burke, 1997 for review), in particular regarding tip-of-the-tongue (TOT) experiences in older adults. TOTs represent retrieval difficulty in which speakers temporarily cannot retrieve (Brown & McNeill, 1966), or are only partially successful in retrieving (Gollan & Brown, 2006), a known word. A widely accepted finding is that older adults experience higher rates of TOTs (e.g., Burke, MacKay, Worthley, & Wade, 1991; Brown & Nix, 1996; Gollan & Brown, 2006), especially for proper names (Burke, Locantore, Austin, & Chae, 2004; Maylor, 1990). Under the IDH, older adults may have increased TOTs for proper names due to activation of irrelevant names and reduced ability to suppress interference from these competitors. If so, older adults should report *more* interfering alternate words ("blockers") that may come to mind during a TOT state. However, older adults reported fewer alternate words during TOTs, and when explicitly primed with alternate names, younger and older adults exhibited equal effects in the opposite direction (such that alternate names cued rather than interfered with retrieval (Cross & Burke, 2004).

Attempts to determine the role of inhibition in *monolingual* language production may be limited by a general consensus that, unlike other cognitive domains, 1) language processing appears to be relatively preserved in aging (e.g., Shafto & Tyler, 2014) and 2) competition for selection may not be very strong within a *single* language and may be limited to the lexical level where reactive control processes (that are not impaired in aging) are primarily involved in resolving competition. Thus, aging deficits in language processing may be magnified when examining *bilingual language selection*, which is arguably more challenging, and can arise at multiple processing levels. A prominent theory of bilingual language processing is the Inhibitory Control Model, or *ICM* (Green, 1998). On this view, bilinguals manage competition between languages by inhibiting whichever language is not currently in use, both at the lexical level, and via a second (independent) global inhibitory control mechanism at the whole-language level.

Supporting the ICM, the dominant language often exhibits greater switching costs. That is, in language-switching tasks, bilinguals name pictures or digits in one language or another based on a cue (e.g., a red cue for one language and a blue cue for the other). Response times are slower when bilinguals are cued to switch versus not switch between languages, exhibiting *switch costs*—that surprisingly, are often larger when switching back into their dominant language than when switching into their nondominant language. This counterintuitive *switch cost asymmetry* is often cited as evidence for inhibitory control (but see Bobb & Wodniecka, 2013): To produce words in the nondominant language, the more dominant language must be inhibited, meaning that, when returning to the dominant language, bilinguals must overcome this inhibition, leading them to exhibit greater switch costs (e.g., Meuter & Allport, 1999; for review see Declerck & Philipp, 2015; Khateb, Shamshoum, & Prior, 2017).

More consistent evidence for inhibitory control (or proactive control; Declerck, 2020) of the dominant language is found in *blocked language-order effects* in behavioral and ERP studies (e.g., Branzi, Martin, Abutalebi, & Costa, 2014; Kreiner & Degani, 2015; Misra, Guo, Bobb, & Kroll, 2012; Van Assche, Duyck, & Gollan, 2013; Wodniecka, Szewczyk, Kalamala, Mandera, & Durlik, 2020). In these studies, bilinguals are tested in just one language at a time, but may exhibit order effects after previously completing a task in the other language (in different testing blocks), especially in the dominant language. Thus, prior use of the nondominant language appeared to interfere with lexical access in the dominant language, which has been observed in different paradigms (e.g., Phillipp & Koch, 2009; see Kroll, Bobb, Misra, Kuo, 2008 for review) and even across longer time-scales (e.g., immersion; Baus, Costa, Carreiras; 2013; Linck, Kroll, & Sunderman, 2009). Furthermore, in a few studies this interference was observed even when nonoverlapping materials (e.g., pictures) were used across testing blocks, implying that bilingual language control is applied globally to the non-target language (Branzi et al., 2014; Kreiner & Degani, 2015; Van Assche et al., 2013; Stasenko & Gollan, 2019; Wodniecka et al., 2020).

Another, even more powerful signature of inhibitory control in bilingual language processing— and the focus of the present study— is found in fully *reversed language dominance* effects. When there is no requirement to switch languages, bilinguals typically respond faster in their dominant language (i.e., in single-language blocks; for review see Hanulová, Davidson, & Indefrey, 2011). In contrast, in mixed-language blocks bilinguals responded more slowly in their dominant than in the nondominant language (Christoffels, Ganuschschak, & Heij, 2016; Christoffels, Firk & Schiller, 2007; Costa & Santesteban, 2004; Costa, Santesteban, & Ivanova, 2006; Heikoop, Declerck, Los, & Koch, 2016; Gollan & Ferreira, 2009; Kleinman & Gollan, 2018; Verhoef, Roelofs, & Chwilla, 2009, 2010; see Declerck, 2020). This counterintuitive finding of reversed language dominance effects is most often explained by assuming that bilinguals apply global inhibition to the dominant language to facilitate production of both languages in the same testing block (Christoffels et al., 2007; 2016; Heikoop et al., 2016; Gollan & Ferreira, 2009; see also Bobb & Wodniecka, 2013 and Decklerck, 2020 for review). Although reversed dominance may serve as strong evidence of inhibition (e.g., Declerck, Kleinman, Gollan, in press; Kleinman & Gollan, 2018), it is not always found, and it is not fully understood what conditions lead it to emerge (Decklerck, 2020 for review).

The Role of Inhibition in Aging Bilinguals' Language Processing

If proactive control declines in older age, and assuming reversed language dominance effects in fact reflect such global control processes, then aging bilinguals should show reduced ability to reverse language dominance relative to younger bilinguals. This phenomenon has not been investigated in aging bilinguals in trial-to-trial picture naming tasks with repeated presentation of a small set of pictures which may be critical for reversed dominance effects to emerge (Kleinman & Gollan, 2018). Two previous studies examined cued language-switching in Spanish-English bilinguals but without repeated presentation of a small set of pictures, and neither younger nor older bilinguals exhibited reversed language dominance (Hernandez & Kohnert, 1999; 2015). Another study repeated a set of pictures and also did not report reversed language dominance (Calabria, Branzi, Marne, Hernández, & Costa, 2015). Finally, a study by Weissberger, Wierenga, Bondi, and Gollan (2012) compared younger and older bilinguals in color-shape and language switching tasks (with digits 1-9 as targets), and did not report on language dominance effects in detail (except in Footnote 1, where they reported a marginally significant interaction such that younger bilinguals exhibited reversed dominance, while older bilinguals did not).

One reason why Weissberger et al. (2012) did not obtain robust support for an inhibitory control deficit was that they did not examine how the effects unfolded over time, but recent evidence suggests that inhibition of the dominant language accumulates over time in mixed-language testing blocks. Kleinman and Gollan (2018) combined data from several language switching experiments into a super-sized dataset (> 400 bilinguals) that made it possible to isolate independently contributions of three key effects. First, bilinguals named pictures in the dominant language increasingly more slowly for each time they had named *any* unrelated picture in the nondominant language, a result that suggests accumulation of language-wide *global inhibition* of the dominant language (Kleinman & Gollan, 2018). Second, a picture was named more slowly in both languages for each time its translation equivalent had previously been produced, suggesting symmetric inhibition between languages at the lexical level (i.e., *local inhibitory control*). Finally, the nondominant language appeared to benefit more than the dominant language from repetition (see also Francis, Augustini, & Sáenz, 2003), which independently contributed to dominance reversal. Given the finding that inhibition may accrue over time, we reanalyzed data from Weissberger et al. as a function of trial number. In these data, younger bilinguals appeared to exhibit increasingly large dominance reversal towards the end of the testing block, while older bilinguals showed an unexpected pattern (increasingly large normal dominance effects), but none of these effects, and critically also not the 3-way interaction between Group, Language, and Trial Number, were significant (*p*s ≥ 0.09).

The Current Study

Several factors might have limited sensitivity for detecting aging effects on language dominance in Weissberger et al. The number of trials in that study was small (n = 80 compared with 108 in Kleinman & Gollan, 2018), and language-switching stimuli were single digits, which elicit smaller switch costs than pictures (Declerck & Philipp, 2015). To address these possible weaknesses, we examined the emergence of dominance reversal over time in younger and older bilinguals using a cued language switching task with repeated presentation of pictures, and with a greater number of trials than in our previous study (Weissberger et al., 2012). To distinguish between reactive control at the lexical level, and global/proactive control at the whole-language level, we presented one set of pictures, henceforth List A, and halfway through the experiment we introduced a new set of pictures, henceforth List B. We hypothesized that if language dominance reverses primarily because of global control, then this inhibition should transfer to the new pictures, leading to dominance reversal for items in both lists. Additionally, if inhibition accumulates throughout the testing block, and is also at least partially specific to the items that have been repeated (i.e., perhaps via reactive inhibition between translation equivalents), then dominance reversal would be greater for List A than for List B items, and in turn List B items would then provide a purer index of global inhibition. Alternatively, repetition might have lexically specific effects in the opposite direction (i.e., facilitating responses, as in Misra et al., 2012) in which case dominance reversal might be greater for List B than List A items.

For aging effects, we predicted that older bilinguals would show reduced ability to reverse language dominance relative to younger bilinguals but that this deficit might be especially pronounced on List B items, which would provide a purer measure of global inhibition (rather than lexical-level effects contaminated by extensive repetition). Finally, given recent evidence that inhibition accumulates with repetition (Kleinman & Gollan, 2018), aging effects might also be modulated by trial number. If dominance reversal continued to increase throughout the block in younger bilinguals, and never emerged in older bilinguals, then group differences in the extent of dominance reversal might be largest towards the end of the testing. Alternatively, if dominance reversal plateaus for younger bilinguals, and/or if older bilinguals rely more on reactive inhibition for repeated items, then aging effects might be smaller for List A items (which would be repeated 16 times in each language by the end of the experiment).

Methods

Participants and Recruitment

Forty-eight younger bilinguals and 25 older bilinguals[12] participated in the study for course credit or monetary compensation. Table 1 shows participant characteristics and demographics. Younger bilinguals were undergraduates at UCSD (ages 18-24). Older bilinguals (ages 62-91) were recruited from a cohort of cognitively healthy aging bilingual controls at the UCSD Alzheimer's Disease Research Center (ADRC; *n*=17) or from the community (*n*=8). Older participants were classified as cognitively healthy by the ADRC criteria using extensive neuropsychological and neurological exams reviewed by two neurologists independently. If recruited from the community, older bilinguals were administered the Dementia Rating Scale (DRS) and the Mini-Mental State Examination (MMSE) and were excluded for scores in the impaired range (see Table 1 for means). To measure age group differences in non-linguistic attention and inhibition, participants completed a Flanker task at the end of the testing session.

Older bilinguals had significantly more years of education than younger bilinguals (but note that ultimate attainment of education level would likely be similar for the two groups given that younger bilinguals were undergraduates at UCSD, and older bilinguals averaged 15 years of education, which is just one year short of an undergraduate degree). As reported in studies showing higher vocabulary scores

[12] We originally recruited 34 total older bilinguals primarily from a pool of healthy control participants at the ADRC. Five were excluded for converting shortly after their participation from a diagnosis of Normal to a diagnosis of Mild Cognitive Impairment, and one to a diagnosis of probable AD. Two participants recruited from the community were excluded for having Dementia Rating Scale scores below 130. Another two participants were excluded for having mean RTs that were extreme outliers in mixed-language blocks. This was determined using an interquartile range (IQR; difference between the 75th and 25th percentiles of the data) outlier labeling method, which is shown to be more robust against outliers than the mean or standard deviation (Hoaglin, Iglewicz, Tukey, 1986). This showed that subject-level RTs for two individuals fell > 3 interquartile ranges (IQR) in their respective group, whereas no extreme outliers were identified in the younger bilingual group. To be most conservative in our exclusion, we used >3 IQR rather than a more liberal 1.5 or 2.2 IQR cut-off as commonly used (e.g., Hoaglin & Iglewicz, 1987). These two outliers were confirmed with a z-score analysis on trial-level RTs across the experiment suggesting extremely slow reaction times in both mixed and single-language blocks.

in aging adults (Verhaegen, 2003 for meta-analysis), older bilinguals had higher picture naming scores than younger bilinguals (in this case in both languages; see also Gollan & Goldrick, 2019). Older bilinguals also reported learning English a few years later relative to younger bilinguals (6.9 vs 3.9; Table 1). Critically, however, bilinguals were matched on degree of bilingualism as measured by the Bilingual Index score (nondominant divided by dominant language) using an objective measure of proficiency in each language (the Multilingual Naming Test; Gollan et al., 2012; Table 1).

Measures and Procedure

A highly proficient native Spanish-English bilingual experimenter administered all the tasks. The MINT is a 68-item picture naming test designed as an objective measure of proficiency in several languages. Participants first named pictures in their self-rated dominant language, followed by the same pictures in the nondominant language. Stimuli from the language switching and Flanker tasks were presented on a MacBook laptop with a 15-in. display using PsychoPy version 1.81 (Peirce, 2007; 2009).

Language Switching

Participants named 20 (10 in List A; 10 in List B) black and white line drawings of pictures repeatedly in Spanish or English based on a visual cue (United States flag for English; Mexican flag for Spanish). Pictures were selected from Gollan and Ferreira (2009) for having high naming accuracy and agreement in both older and younger adults (>86%). Seven additional pictures that exhibited large dominance reversal effects in Kleinman and Gollan (2018) were also included. Assignment of items to List A (first half of the experiment) or List B (second half of the experiment) was counterbalanced across participants: For half of the participants, pictures 1-10 were in List A and pictures 11-20 were in List B, whereas for the other half of the participants, pictures 1-10 were in List B and 11-20 were in List A. Pictures were presented in a pseudorandom order such that the same picture was never shown on consecutive trials. Also, each presentation of a given picture in a given condition and block was relatively spaced out such that it had to appear in every condition once (e.g., dominant language – switch trial) before it appeared in any condition a second time (e.g., Picture 1 appeared in trial 1, 11, 24 and 38). Bilinguals were cued to name pictures in each language 50% of the time, with a 50% switch rate in each language. The maximum number of switch trials in a row was limited to 4. A practice ('filler') item was presented as the first trial of every block and was discarded from analyses. Four item lists were used so that item groups and the sequence of language cues were counterbalanced across subjects.[13]

Table 2 illustrates the block structure. Participants completed 12 practice trials before the first single-language block and before the first mixed-language block (with the same trial structure). The first half of the experiment consisted of List A items only using a Rubin and Meiran (2005) sandwich design. Participants first completed two single-language blocks (naming in only English or only Spanish) of 20 trials each (40 critical trials total). Next, they completed two mixed blocks of 80 trials each (160 critical trials total) with a short break allowed between blocks. Finally, they named another set of two single-language blocks (40 trials total) to complete the 'sandwich' design for List A items, with language counterbalanced (i.e., English-first or Spanish-first, which was reversed in the second set of single-language blocks). In the first half of the experiment each of the 10 List A critical pictures was repeated 16 times (8 times in each language) across the 160 critical trials; in the single-language blocks each picture was repeated 4 times in each language (i.e., a total of 8 times) across the 80 trials.

The second half of the experiment involved an additional and final repetition of List A pictures intermixed with 10 new (previously unseen) pictures (i.e., List B). Each of the 10 critical List B items was repeated 8 times (4 times in each language) across the 80 critical List B trials (intermixed with another 80 List A trials not included in the above count). In the List B single-language blocks, each picture was repeated twice in each language (total of 4 presentations per picture). The second half of the experiment began with single-language naming of 40 trials of List B items followed by a final set of two mixed blocks comprised of 80 trials each (i.e., 160 critical trials total; 80 List A items and 80 List B items randomly intermixed). Within each block, there was no restriction on how many List A items appeared before the presentation of a List B item. As before, participants were able to take a short break after 80 trials.

[13] In our final dataset, each counterbalancing group had 12 younger bilinguals and 6 (or 7) older bilinguals.

Every trial began with a fixation cross presented for 500 ms. A language cue (flag) appeared on the screen above the fixation cross for 500 ms. This relatively long preparation time was chosen to minimize the effects of any possible age differences in cue processing. Target pictures then appeared in the center of the screen while the cue remained on screen. The cue and target remained until the bilingual responded, or for a maximum of 3000 ms. There was an 850 ms inter-stimulus blank screen prior to the onset of the next trial (see Figure 1 for procedure).

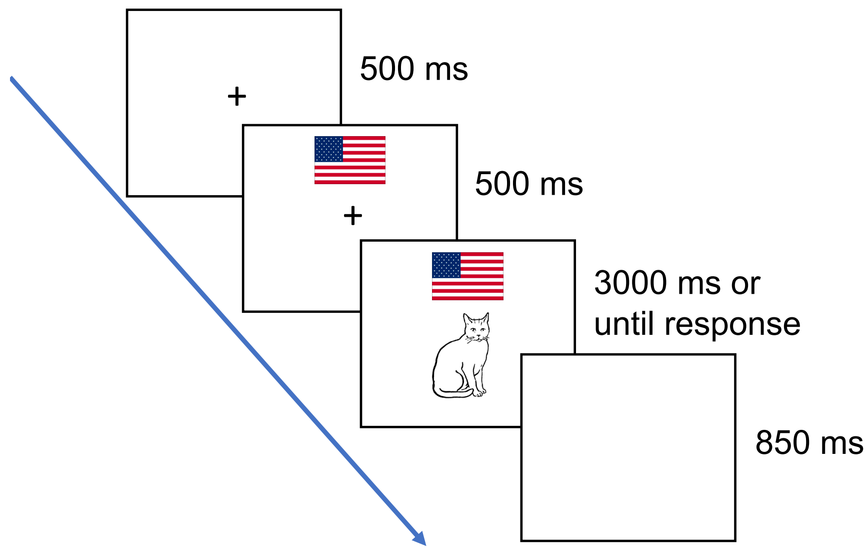

Figure 3.1. *Cued Language Switching Task. Experimental Design*

Non-linguistic Control

We included the flanker test as a nonlinguistic measure of inhibitory control. Following Wardlow, Ivanova, and Gollan (2014), a center arrow was surrounded by two horizontal lines or arrows on each side. Targets were 32 congruent (five arrows pointing in the same direction), 32 neutral (a single arrow flanked by lines without arrowheads), and 32 incongruent displays (a center arrow flanked by arrows pointing in the opposite direction). These were evenly divided between left- and right-pointing center arrows, and were presented in random order. Participants indicated the direction of the central arrow by pressing the appropriate key (“z” or “?”) with their left or right index finger, respectively. Trials included a 500 ms central fixation point, followed by the target stimulus until a response was recorded.

The inter-trial interval was 500 ms. Participants completed practice (six neutral trials followed by six congruent trials, then six incongruent trials, and then six trials with equal numbers of the different conditions in random order). All older bilinguals and 24 younger bilinguals completed 3 testing blocks with a short break in between (96 x 3 = 288 trials). The other 24 younger bilinguals only completed 1 testing block (96 total trials) due to an experimenter error.

Statistical Analyses

Across all included participants, 8,426 and 22,149 trials from the mixed- and single-language blocks, respectively, were submitted to RT analyses. Trials with incorrect responses or voice key errors, and trials that were faster than 250 ms, were excluded. This resulted in a total exclusion of 5% of the younger bilinguals' data and 5% of the older bilinguals' data for RT analyses. The RT data were analyzed using linear mixed-effects regression modeling (lme4 v. 1.1.21; Baayen, Davidson, & Bates, 2008) using R (version 3.6.3; R Core Team, 2017), and denominator degrees of freedom were estimated via the Sattherthwaite approximation (lmerTest v. 3.1-0; Kuznetsova, Brockhoff, & Christensen, 2017). In the omnibus model, fixed effects (and contrast weights) for analysis of mixed blocks included Language (Dominant = -0.5; Nondominant = +0.5), Trial Type (Stay = -0.5; Switch = +0.5), Group (Younger bilinguals = -0.5; Older bilinguals = +0.5), List (List A = -0.25; List B = +0.75), and all possible interactions between these factors. For the matching error analysis, we used logistic regression (glmer; generalized linear mixed models) with the same fixed factors. Error trials were coded as "1" and correct trials were coded as 0. An additional factor, *Trial Number* (range 1-320; values were centered and scaled), was added to one model to examine the influence of repetition in mixed-language blocks for List A items across the whole experiment. The 'emmeans' package in R was used for simple main effects and interaction contrasts.

For all reported models, we used a consistent three-step data-fitting strategy: (1) A model with a maximal random effects structure was fitted: random intercepts, all within-factor random slopes and their interactions, and correlations between random slopes. If this model did not converge (which was the case for all initial models), (2) we removed correlations between random slopes. If the resulting model still did not converge or converged with boundary issues (which was the case for all models) (3) we identified random slopes that accounted for less than 1% of the variance of their associated random factors, and then simultaneously removed all such slopes from the model (Bates, Kliegl, Vasishth, & Baayen, 2015). Trial-level data and analysis scripts are publicly available at osf.io/8h4dq

Results

Table 3 shows means and standard deviations for all conditions of interest for the language switching task.

Single-Language Blocks

We began by examining standard language dominance effects within List A single-language blocks for the first 40 trials (i.e., prior to language-mixing trials) in separate Group × Language analyses for reaction times and errors. Bilinguals responded more quickly in the dominant than in the nondominant language (a significant main effect of Language; $M = 786$ vs 859 ms; $B = 82.4$; $SE(B) = 16.3$; $t(69) = 5.1$; $p < 0.001$), and younger bilinguals responded more quickly than older bilinguals (a significant main effect of Group; $M = 787$ vs 887 ms; $B = 98.5$; $SE(B) = 22.9$; $t(70) = 4.3$; $p < 0.001$). The two-way interaction was not significant ($B = 49.8$; $SE(B) = 34.3$; $t(55) = 1.5$; $p = 0.15$). An analysis of errors provided converging evidence, revealing that bilinguals made fewer errors in the dominant than in the nondominant language (a significant main effect of Language; $M = 0.01$ vs 0.04; $B = -0.48$; $SE(B) = 0.50$; $z = 2.1$; $p < 0.05$). The two-way interaction was not significant ($B = -1.00$; $SE(B) = 0.86$; $z = -1.2$; $p = 0.25$). Importantly, assignment of different pictures to List A versus List B (equivalent of first versus second half of the experiment) was counterbalanced between participants. Thus, it is not necessary to examine language dominance effects in single-language blocks on List B items, which were presented only *after* language-mixing (which could affect language dominance effects). Note that we included List B single-language blocks only so that bilinguals would have equivalent practice naming List A and List B items in single-language blocks prior to their inclusion in mixed-language blocks.

Mixed-Language Blocks

Table 4a and Figure 2 show the results of the mixed-language blocks analysis of RTs. Older bilinguals responded more slowly than younger bilinguals, a significant main effect of Group (*M* = 933 vs 811 ms). Bilinguals also responded more slowly on List B than List A items, a significant main effect of List (*M* = 871 vs 846 ms); and responded more slowly on switch versus stay trials, a significant switch cost indicated by a main effect of Trial Type (*M* = 884 vs 822 ms). Of greatest interest, there was a significant interaction between Language × Group such that younger but not in older bilinguals exhibited reversed language dominance. Planned comparisons collapsing across Trial Type and List revealed that whereas younger bilinguals named pictures more slowly in the dominant than in the nondominant language (*M* = 822 vs 799 ms; *B* = 28.6, *SE*(*B*) = 8.0, $p < .001$), older bilinguals exhibited no significant language dominance effects (*M* = 927 ms for the dominant language vs *M* = 938 ms for the nondominant language; *B* = -6.3, *SE*(*B*) = 10.6, *p* = 0.55). Finally, older bilinguals exhibited larger switch costs relative to younger bilinguals (a significant Group × Trial Type interaction (*M* = 78 vs 56 ms).[14]

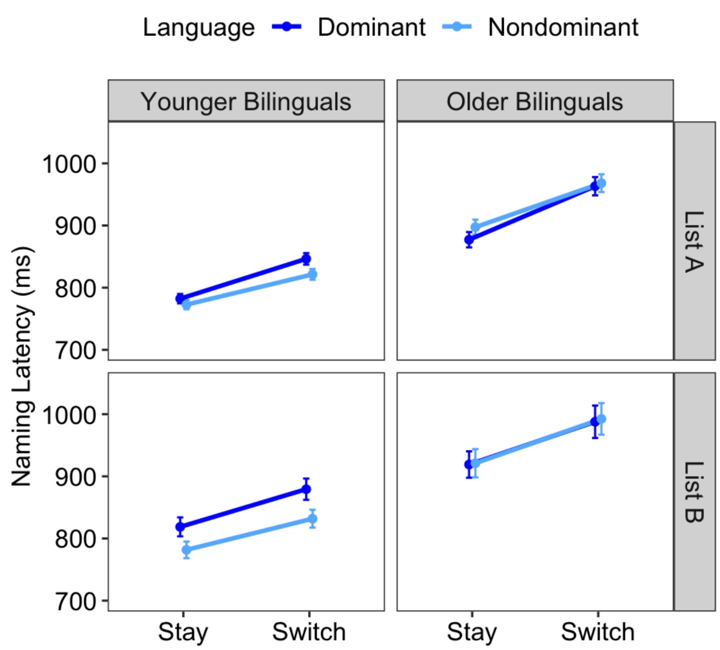

Figure 3.2. *Naming Latencies in All Mixed-language Blocks (i.e., Language-Switching Blocks) Plotted by Trial Type (x-axis) and Language, Separately by Age Group and Picture List***.** Error bars represent 95% confidence intervals.

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[14] Given a marginal List × Language interaction, we examined this in younger bilinguals alone. Although reversed dominance was significant in both lists, it was larger in List B than List A (a significant interaction between List and Language; *B* = -24.1, *SE*(*B*) =9.2, *t*(18)=-2.6, *p* = 0.018).

Errors

Table 4b presents the output of a matching error analysis collapsing all error types. Error rates were generally low in mixed-language blocks (4%). The majority of errors made in mixed-language blocks across both age groups were intrusions 43% (i.e., naming the picture in the wrong language); 24% were partial intrusions; and 29% were incorrect, no-response, or don't-know responses. Older bilinguals made significantly more errors than younger bilinguals (M = 0.05 vs 0.03) and bilinguals made more errors on switch versus stay trials (M = 0.06 vs 0.02)—significant main effects of Group and Trial Type.

Reversed Dominance in Younger Bilinguals for List A versus List B items

To examine whether younger bilinguals reversed language dominance significantly more for items that had already been named repeatedly in mixed-language blocks than for items for less practiced items, we performed two comparisons between List A and List B items. First, we compared Lists A and B within the second half of the experiment (Blocks 3 and 4) to examine the effects of local inhibition on language dominance. In these blocks, List A items had been named many more times previously than List B items, so any item-specific component of reversed dominance effects should affect List A more than List B (while global inhibition would be equal across lists). Second, we compared List A items from the first Block (before intermixing lists in the first half of the experiment) to List B items (in the second half) to examine the effects of global inhibition on language dominance (with lexically-specific inhibition equated across lists). In these blocks, List A and List B items had been previously named the same number of times. However, List B (in Blocks 3 and 4) was preceded by more language mixing than List A (in Block 1), so global changes to the balance of language activation had more time to accumulate prior to List B and should thus affect those items more.

The results of these analyses are shown in Figure 3. For these analyses, we removed trial type to increase power given that the omnibus model did not show any interactions with this factor. This analysis revealed a significant interaction between Block and Language (B = -25.6 ms, $SE(B)$ = 11.9 ms; $t(18)$ = -2.1, p = 0.045). Simple main effects suggested that bilinguals responded slower in the dominant than the nondominant language in the second half of the experiment for both List A and List B items (M = 825 vs

804 ms; *SD* = 234 vs 229 ms for List A and *M* = 848 vs 806 ms; *SD* = 252 vs 213 ms for List B; $p = 0.02$ and < 0.001, respectively) but not in the first half (i.e., Block 1: *M* = 805 vs 790 ms; *SD* = 219 vs 209 ms; $p = 0.12$). Custom interaction contrasts revealed that reversed language dominance in List B items was both significantly bigger compared to Block 1 List A items ($B = -12.7$, $SE(B) = 5.9$, $t(18) = -2.1$; $p = .046$) and compared to List A items in the second half ($B = -10.1$, $SE(B) = 5.0$, $t(150) = -2.0$; $p = .046$). Importantly, the greater dominance reversal effect in List B relative to Block 1 of List A was driven by slower responses in the dominant language in List B than List A (*M* = 848 vs 805 ms: *SD* = 252 vs 219 ms; $B = -43$; $SE(B) = 13.4$; $t(59) = -3.3$; $p < 0.01$), whereas younger bilinguals named pictures in the nondominant language at a similar speed across lists ($p = 0.37$).

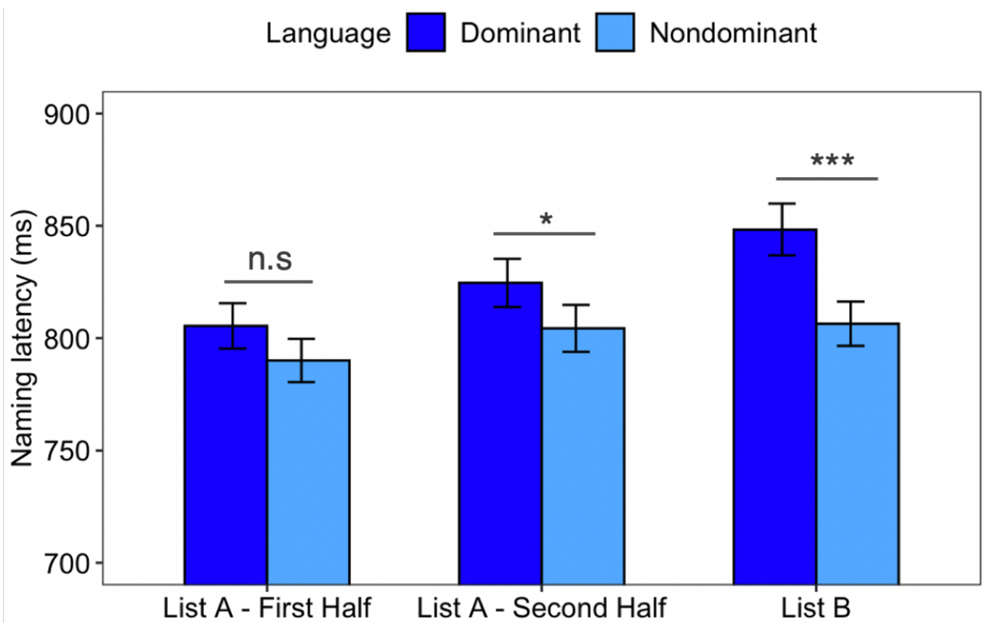

Figure 3.3. *Younger Bilinguals' Naming Latencies Plotted Separately by List A items (Before Intermixing Lists; First Half of the Experiment) and List A and B Items When Intermixed (Second Half of the Experiment).* Asterisks signify where reversed dominance effects are significant (* $p < .05$; *** $p < .001$).

Having found that younger but not older bilinguals exhibited greater language dominance reversal for List B items, we repeated the same analysis in older bilinguals to examine if the aging deficit in reversed dominance was larger in List B than in List A. Overall the interaction between Language × Block in older bilinguals was not significant ($p = 0.30$) and planned contrasts revealed no significant language dominance effects in any of the three blocks ($ps \geq 0.21$).

Effects of Repetition in Mixed-Language Blocks

To test whether inhibition increases over time and whether this might have modulated aging effects, we conducted a final analysis with all presentations of List A pictures across the four mixed-language blocks, and with the linear effect of Trial Number as an additional factor (removing Trial Type to avoid overly complex models). The linear effect of trial number was not significant and did not interact with other factors (see Table 5; see Appendix Figure A which plots trial-level data by block). We examined the same model in younger bilinguals only and found a significant main effect of trial number (B=9.2; $SE(B)$ = 4.3; $t(47)$=2.1; $p < 0.05$), which did not interact with language ($p = 0.70$).[15]

Discussion

The results of the present study revealed several key findings. First, in single-language blocks administered prior to the cued language-switching task, both younger and older bilinguals exhibited normal (not reversed) language dominance effects, and language dominance effects were also equally strong in young and older bilinguals. By contrast, in mixed-language blocks, younger but not older bilinguals exhibited significantly reversed language dominance effects. Second, in younger bilinguals dominance reversal effects were larger in List B than in List A items, an effect that seemed to be driven by slower responses in the dominant language in List B relative to List A. Third, we did not find that inhibition accumulates indefinitely with repetition or that the aging deficit is largest at the end of the experiment. There was a significant effect of trial number for younger bilinguals alone such that List A responses slowed across blocks. However, this effect was present across both languages, perhaps suggesting effects of fatigue. In contrast, older bilinguals' responses initially sped up with repetition and only began to slow toward the end of the experiment. Finally, older bilinguals exhibited significantly larger switch costs than younger bilinguals[16].

[15] We also added a quadratic effect of trial number to the model with both bilingual groups. This model revealed a significant Group X Trial Type (quadratic) interaction (B=9.6; $SE(B)$=4.6; $t(70)$=2.1; $p < 0.05$). This interaction suggested a significant quadratic effect of overall naming latencies in older bilinguals ($p = 0.009$), but not in younger bilinguals ($p = 0.59$) who instead showed more of a linear trend (see above analysis).

[16] However, the age-related increase in switch costs was not significant after applying a z-score transformation, or in an analysis of proportional costs (i.e., (switch – stay)/stay; see Weissberger et al., 2012) to control for baseline

Global Inhibition of the Dominant Language

Our finding of reversed language dominance effects in younger bilinguals replicates previous findings (Christoffels et al., 2007; Costa & Santesteban, 2004; Costa et al., 2006; Gollan & Ferreira, 2009; Heikoop et al., 2016; Kleinman & Gollan, 2016; 2018; Verhoef et al., 2009; for review see Declerck, 2020), and generally fits with a number of studies which revealed costs to the dominant language after prior testing in the nondominant language (e.g., Branzi et al., 2014; Misra et al., 2012; Declerck, 2020 for review) and that these costs transfer to novel, unpracticed items (Christoffels et al., 2016; Wodniecka et al., 2020). Such studies might have sometimes failed to observe a clear inhibitory effect on the dominant language because such inhibition may fade after switching back to a block only in the dominant language. Thus, a unique feature of our study design was the introduction of a new list of pictures halfway through the mixed-language blocks. This manipulation indexed the extent to which inhibition of the dominant language had accumulated during mixed-language blocks without requiring inhibition to survive across single-language blocks.

Of particular interest, reversal of language dominance not only transferred to List B items, it was even overall greater in List B than in List A within younger bilinguals (and because assignment of specific pictures to each list was counterbalanced between participants, this was not an artifact of particular items). If dominance reversal exclusively reflected the magnitude of global inhibition, it should have been equal for List A and List B items. We speculate that extensive repetition of List A items may have weakened dominance reversal, perhaps facilitating responses in the nondominant language more than it increased competition for selection between translation-equivalents, although it is not entirely clear how this would reduce dominance reversal. Note that by the time participants encountered List B items they already had extensive practice with language switching, and had time for global inhibition to accumulate – but the relatively larger effect on List B suggests that extensive repetition of List A items

slowing (see Table 4). We did not examine mixing costs given the absence of a complete design for List B items, but mixing costs in the first half of the experiment for List A items only were equivalent across groups; see Appendix—Table A).

served to *offset* instead of magnify lexical level competition for selection between languages, and reactive inhibition between translation equivalents. However, this would still not explain why dominance reversal in List B was greater than the *initial* block of List A items (because in this comparison the effects of repetition for specific items were equated). Thus, an alternative possibility is that younger bilinguals over-applied inhibition to less practiced items, though this would require distinguishing old from new list items in fractions of a second and modulating the amount of inhibition trial-to-trial, which seems rather unlikely. We tentatively conclude that dominance reversal reflects global inhibition of the dominant-language as a whole, much more than lexical-level inhibition.

We did not replicate the finding that inhibition continuously accumulates over time as in Kleinman and Gollan (2018). Several methodological differences between the two studies could have resulted in this, including a smaller sample size, inclusion of four mixed-language blocks instead of one as in Kleinman and Gollan, and controlling the lag between repetitions of pictures in the current study which resulted in a different statistical analysis.

The Inhibitory Deficit Hypothesis

The results of the present study provide clear evidence in support of the IDH, and perhaps the clearest evidence reported thus far in the literature for an inhibitory control deficit in aging with language production as the primary task. This is consistent with our suggestion above that bilingual language production may entail greater control requirements than monolingual speech production (contra Costa, Pannunzi, Deco, & Pickering, 2017; Paap & Greenberg, 2013). Given our conclusion that reversed language dominance effects largely reflect inhibitory control at the whole-language level, the finding of an aging deficit therein is also generally consistent with previous suggestions that proactive control is impaired in aging and that bilingual language control may rely on domain general proactive control (though it is also possible that domain-general and language-specific global control processes exhibit independent impairments in aging (as argued by Jylkkä, Lehtonen, Lindholm, Kuusakoski, & Laine, 2018)[17].

Interestingly, although older bilinguals did not reverse language dominance, they also did not exhibit significant *normal language dominance* effects in mixed-language blocks either (though numbers trended in this direction), whereas they did in single-language blocks, prior to language mixing. Additionally, although the interaction between Language and Trial Number was significant on its own in young but not in older bilinguals, the interaction with Group did not approach significance. These considerations suggest that older bilinguals may have been attempting to inhibit the dominant language and were partially successful in doing so by the end of the experiment, shown in Figure 4 which summarizes dominance effects across the experiment.

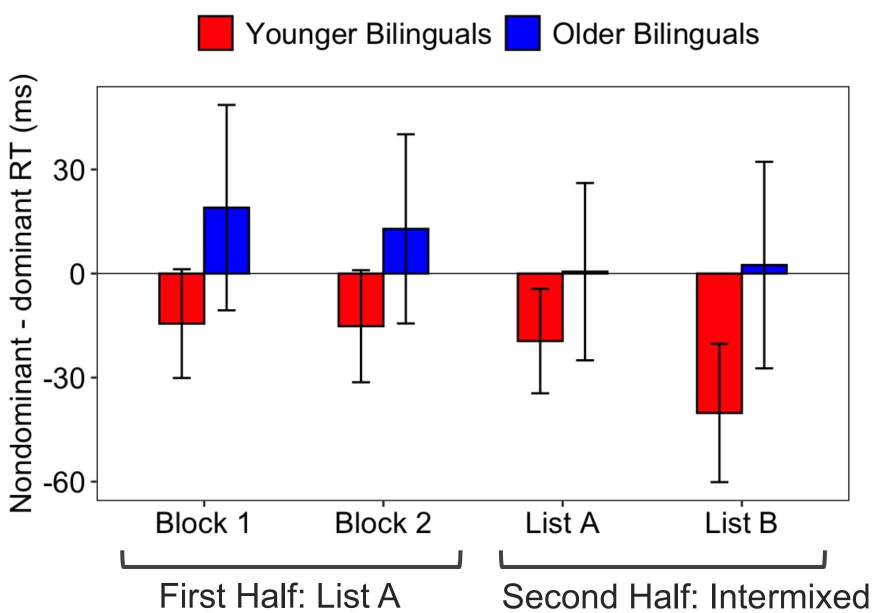

Figure 3.4. *Summary of Language Dominance Effects (i.e., Nondominant – Dominant RTs) by Experimental Block***.** Error bars represent 95% confidence intervals.

[17] Our results cannot be attributed merely to cognitive slowing in aging (e.g., for review see Verhaeghen, 2011), given that age-difference in language dominance effects remained significant after controlling for baseline slowing with z-score transformations (note this is not surprising because in these comparisons young bilinguals exhibited larger effects despite having faster response times than older bilinguals; see footnote in Table 4).

A question that arises given our conclusion that List B provided a purer index of global control than List A, and that the aging deficit is localized primarily at the level of global control, is why the aging deficit was not significantly larger for List B than List A items. Although this appears to be the case when visually examining Figure 4, the three-way interaction was not significant (Table 2). To further explore this issue, we examined the aging effect on dominance reversal within each list alone (i.e., the Group X Language interaction), and although both contrasts were significant (B = - 26.9; $SE(B)$ = 13.0; p = 0.042 for List A and B = - 42.9; $SE(B)$ = 16.1; p = 0.009 for List B), the effect size for List B was relatively larger than for List A. Cautiously interpreting this relative difference, a magnified aging deficit for List B relative to List A items (which were repeated much more in the course of the entire experiment) could suggest that intact lexical repetition allowed older bilinguals to partially compensate for a deficit in global control. On this view, we would have to assume that the lack of a 3-way interaction either reflected an absence of power to detect it, or the presence of more complex interactions between lexical-level and global control that obscure the modulation of aging effects by list type.

The absence of dominance reversal for older bilinguals in the present study is at odds with Gollan and Ferreira (2009) who found reversed dominance for older bilinguals in a voluntary language switching paradigm (i.e., ‘name the picture in whatever language comes to mind’), and another study in which speech errors were induced by having bilinguals read aloud mixed-language paragraphs (Gollan & Goldrick, 2016). Reversed dominance effects in voluntary switching may simply reflect item selection strategies wherein bilinguals choose to speak in the nondominant language only to produce relatively easy names, leaving all the difficult items to be produced in the dominant language (see also Gollan, Kleinman, & Wierenga, 2014). In the read-aloud task, reversed language dominance was reported only on *intrusion* errors in which bilinguals spontaneously translated written words (e.g., saying “the” instead of “el” in the sentence “Throughout the Land of the Pig River, el name Mrs. Peace was very well known by almost everyone”; Gollan, Schotter, Gomez, Murillo, Rayner, 2014; see also Kolers, 1966). Whereas dominance was reversed in this study when considering the language of the language-switched words, language dominance effects were normal in this study if considering the language of paragraphs. That is, bilinguals produced the most intrusions when reading aloud paragraphs written mostly in the nondominant language with switches to the dominant language. Follow-up studies revealed the same pattern of language dominance effects even in bilinguals with Alzheimer's disease, who likely had pronounced deficits in inhibitory control — suggesting that a revised interpretation of dominance reversal effects in this task may be warranted (Gollan, Stasenko, Li, Salmon, 2017; Gollan, Li, Stasenko, Salmon, 2020). Alternatively, inhibitory control, and 'default-language selection' in the read-aloud task might be relatively intact in aging and AD because of support from sentence context (Gollan & Goldrick, 2018).

Is Failure to Exhibit Reversed Language Dominance Really a Deficit?

A reasonable question is whether the absence of dominance reversal should be taken as evidence of a processing deficit, or if it could instead reflect an aging-related difference in some other cognitive process. A relevant consideration here is that reversed dominance might not be more efficient. Investigating this matter, in a recent reanalysis of a large language-switching dataset (> 400 bilinguals) we asked if reversed language dominance was associated with faster responses (Declerck et al., in press). This analysis revealed a U-shaped curve such that larger dominance reversal and larger normal dominance effects were associated with slower average response times in mixed-language blocks, while smaller dominance effects were associated with faster responses overall. Thus, dominance reversal appears to reflect the results of a global control process that is blind to some degree to the amount of control that is needed to maximize efficiency in mixed-language naming blocks. This puts a potentially different spin on the 'failure to reverse dominance' possibly suggesting that older bilinguals—who have had many more years of managing dual-language activation—might be better able to gauge (whether implicitly or explicitly) how much proactive control they need to apply to keep both languages about equally accessible. This idea is consistent with aging studies outside the domain of language which suggested that what seems to be a deficit can sometimes instead reflect a processing advantage or difference in priorities and strategic approach (e.g., Amer & Hasher, 2014; Kemper, Kynette, Rash, & Sprott, 1989; Ramscar et al., 2014; for reviews see Amer, Campbell, & Hasher, 2016; Kavé & Goral, 2017). Broadly, this invites further investigation of *why* older bilinguals seemed to exhibit different effects than younger bilinguals and to consider the influence of compensatory and efficiency strategies *within* each group.

Some independent evidence that older bilinguals' failure to reverse language dominance in the present study does reflect a cognitive control deficit was our observation of larger flanker effects in older bilinguals (incongruent-neutral RT; see Table 1), a task we previously found to be associated with intrusion errors in aging bilinguals completing the verbal fluency task (Gollan, Sandoval, & Salmon, 2011) [18]. Additionally, older bilinguals produced more intrusion errors (i.e., naming the picture in the wrong language) in mixed-language blocks (M proportion of errors= 0.04 vs 0.02; SD = 0.20 vs 0.15; B =0.63; $SE(B)$ = 0.18; z = 3.6; p < 0.001). Some additional evidence for a possible deficit in cognitive control was an age-related increase in switch costs (replicating Weissberger et al, 2012; de Bruin, Samuel, & Duñabeitia, 2020). However, this effect did not survive an adjustment for age-related slowing and the age-related increase in language switch costs is not found consistently in the literature (see Calabria et al., 2015; Hernandez & Kohnert, 2015). Although aging deficits in inhibitory control have been challenged (e.g., Verhaeghen, 2011) and in particular on the flanker test—aging deficits in two tasks (go/no and stop-signal tasks) that measure ability to *inhibit a dominant response* might be more robust (Rey-Mermet & Gade, 2018; Rey-Mermet, Gade & Oberauer, 2018). Thus, accumulating evidence seems to suggest that aging primarily affects the ability to inhibit a dominant response, and speculatively this could be related to older bilinguals' failure to reverse language dominance in the present study.

The absence of dominance reversal in older bilinguals is perhaps most similar to previously reported failures to show negative priming (e.g., Kane et al., 1994). That is, older adults may keep both relevant and currently irrelevant responses jointly active (in this case the dominant language is not

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[18] We also explored if measures of linguistic and nonlinguistic control (i.e., switch costs, language intrusion errors, flanker task effects) were correlated with language dominance effects using bivariate correlations within each group. However, none of these correlations survived adjustment for multiple comparisons, and the strongest correlation (which was between number of intrusion errors and switch costs in older bilinguals, r = 0.42; p < 0.05) became null after removing two visual outliers.

inhibited) which could be an aging-related compensatory strategy, or a difference in language acquisition and use over a lifetime (note that bilinguals were matched for bilingual index scores, but differed in some background characteristics; see Table 1). The proposal of an aging deficit in proactive control is consistent with aging effects on the AX-CPT task (Cohen et al., 1999)[19]. Several studies found that older adults showed both performance declines in sensitivity to context, and counterintuitively, performance advantages related to a failure to apply proactive control (Braver et al., 2001; Braver et al., 2007; Braver, 2012; but see Xiang et al., 2016). However, it is unclear what motivates age differences given uncertainty regarding what leads younger bilinguals to exhibit reversed language dominance (i.e., it is not necessarily more efficient; Declerck, et al., submitted). While a growing body of evidence suggests that older adults may fail to spontaneously apply effective strategies in various cognitive domains (e.g., Dunlosky & Hertzog, 2001), additional research would be needed to confirm the association (e.g., to this end, it might be useful to investigate if older bilinguals could be trained to reverse language dominance in switching and if this would improve their overall efficiency or not; e.g., see Paxton et al., 2006 who demonstrated older adults can shift to a more proactive control strategy on the AX-CPT task with training).

An Activation-based Explanation for Reversed Language Dominance?

We have assumed reduced inhibition of the dominant language in older bilinguals and intact inhibition in younger bilinguals as the primary mechanism that accounts for the observed group differences. An alternative explanation is that bilinguals apply extra-*activation* of the nondominant language, which in turn produces interference (e.g., Bobb & Wodniecka, 2013; Koch, Gade, Shuch, Phillipp, 2010; Verhoef et al., 2009) or possibly a combination of both activation and inhibition (Branzi et al.,, 2014; for discussion see Declerck & Philipp, 2015). Our data present at least one challenge for the

[19] In this task, participants respond by pressing one button when a target is presented and a different button when any other stimulus is presented. Although the typical target letter is X, there is an additional constraint that X is only a target when preceded by the letter A but not B. When A-X pairs are made more frequent, there will be a prepotent tendency to respond to any stimulus that follows A, with the expectation that it will be the target X. However, when the letter following the A is Y or a different letter, the participant must inhibit the tendency to respond. Thus, the AX-CPT task measures ability to maintain a goal (i.e., that X must follow A to be a target) and ability to process context (i.e., if B is presented, the next letter cannot be a target).

activation-only account. Dominance reversal in our study was greater for List B than List A and when we directly compared responses in the two lists this difference was driven by the dominant language. That is, the dominant language was slowed by language mixing (in List B than in List A), whereas the nondominant language did not become faster (which is expected on the activation account). Second, under the activation account, activating the nondominant language should be difficult for bilinguals with lower nondominant language proficiency. However, in a newly published study from our lab with a similar bilingual population, lower proficiency bilinguals exhibited the *greatest* change in reversed dominance when evaluating single versus mixed language blocks (Declerck, Kleinman, & Gollan, in press). The activation-only account faces additional challenges discussed in Declerck et al., in press; Gollan & Goldrick, 2018; Kleinman & Gollan, 2018).

Conclusion

Our findings provide unique evidence that bilinguals globally inhibit the dominant language to switch languages and that this proactive control ability decreases in aging. Although the Inhibitory Deficit Hypothesis (IDH: Hasher & Zacks, 1998, Hasher, 2015) has been criticized, it provides ready explanation of our findings. It is possible that a bilingual language switching task requires greater inhibitory control, or control at a higher processing level (proactive instead of reactive) relative to monolingual speech production, but it might also be possible to observe similar aging deficits in monolinguals with a different task than previously used. Although the concept of an inhibitory deficit in aging continues to be debated, it is clear that more work is needed to fully characterize both aging-related changes in nonlinguistic inhibitory control. Similarly, it has recently been suggested that inhibition is not a domain that should show a bilingual advantage (e.g., Bialystok, 2017). However, research on bilingual language processing strongly implicates inhibition, including the work presented herein. It is also noteworthy that switch cost asymmetries do not appear to be a reliable measure of inhibition (see also Chrisoffels et al., 2016), suggesting that increased response times in the dominant language might be a better signal of inhibition. Going forward, the most fruitful approach to reveal how executive control operates in concert with the language system (in bilinguals and monolinguals alike) might be to examine relationships between linguistic and nonlinguistic control processes more directly (by interleaving tasks; Adler et al., 2020; Wu & Thierry, 2013), and to continue to specify more precisely the different mechanisms of bilingual language control, which appear to function at multiple processing levels that can be better revealed with tightly woven experimental manipulations that provide more rigorous tests of hypothesized relationships across domains.

Tables

Table 3.1. *Participant Demographics, Language Background Characteristics, and Cognitive Performance*

	Younger bilinguals (*n*=48)		Older bilinguals (*n*=25)		*p*-value*
% Female	85		72		.29
% Right-handed	88		88		1.0
% Hispanic/Latino(a)	98		100		1.0
	M	*SD*	*M*	*SD*	
Age	19.9	1.4	73.0	7.3	<.001
Education	13.5	1.1	15.3	2.7	<.01
Avg. parental years of education	11.1	4	10.1	4.9	.39
Age first exposure to English	3.9	3.4	6.9	7.5	<.05
Age first exposure to Spanish	0.1	0.6	0.3	1.5	.45
% grow up using English	49.4	21.3	42.1	34.4	.26
% current using English	81.7	18.5	63.7	31.7	<.01
Self-rated English proficiency [a]	6.5	0.7	6.3	0.7	.23
Self-rated Spanish proficiency [a]	6.0	0.7	5.7	1.4	.13
MINT					
Dominant	60.9	2.9	65.1	2.1	<.001
Non-dominant	47.2	8.8	52.6	10.3	<.05
English	59.5	4.8	63.2	4.1	<.01
Spanish	48.6	9.9	54.6	11.7	<.05
Bilingual Index [b]	0.77	0.1	0.81	0.2	.34
MMSE	--	--	28.7	1.8	--
DRS-2	--	--	137.5	3.7	--
Flanker Test					
Neutral RT	431	52	627	119	<.001
Congruent RT	443	59	667	142	<.001
Incongruent RT	471	58	713	169	<.001
Neutral Errors	0.01	0.01	0.00	0.01	0.42
Congruent Errors	0.01	0.01	0.01	0.01	0.62
Incongruent Errors	0.03	0.04	0.02	0.03	0.12
Incongruent-Congruent (ms)	29	23	47	58	.06
Incongruent-Congruent (% error)	0.02	0.04	0.01	0.02	.13
Incongruent-Neutral (ms)	40	23	87	68	<.001[c]
Incongruent-Neutral (% error)	0.02	0.04	0.01	0.02	.16

Note. MINT=Multilingual Naming Test; DRS-2 = Dementia Rating Scale-Second Edition; MMSE = Mini-Mental State Examination. *p*-values correspond to t-tests for continuous variables or Pearson's Chi-square tests for categorical variables.
[a] Self-rating was based on a 7-point scale. 1 = almost none, 2 = very poor, 3 = fair, 4 = functional, 5 = good, 6 = very good, and 7 = like native speaker.
[b] Bilingual Index = Nondominant/Dominant
[c] This age-group difference in the flanker effect survived a baseline adjustment for speed (i.e., (incongruent RT-neutral RT)/neutral RT; t (72) = 2.3; p = 0.02)

Table 3.2. *Structure of the Language Switching Experiment*

Experimental Half	Block Type	Block ID	Picture List	*N* trials
First	Single	Block X	A	40
	Mixed	Block 1	A	80
	Mixed	Block 2	A	80
	Single	Block Y	A	40
Second	Single	Block Z	B	40
	Mixed	Block 3	A and B	40A, 40B
	Mixed	Block 4	A and B	40A, 40B

Note. Single-language blocks (i.e., "Single") are labeled as X-Z and mixed-language blocks (i.e., "Mixed") are numbered 1-4.

Table 3.3. *Means and (Standard Deviations) of Reaction times in the Language Switching Tas*

3a. RTs		All Mixed-Blocks List A			All Mixed Blocks - List B		
Group	Language	Stay	Switch	Switch Cost	Stay	Switch	Switch Cost
Younger	Dominant	782 (205)	846 (247)	64 (64)	819 (239)	879 (263)	61 (67)
	Nondominant	773 (200)	821 (230)	49 (43)	782 (206)	832 (218)	72 (80)
Older	Dominant	877 (239)	963 (276)	87 (52)	919 (238)	988 (286)	78 (100)
	Nondominant	897 (236)	968 (270)	70 (64)	921 (253)	992 (278)	50 (51)
		List A – First Half Only			List B		
		Single	Stay	Mix Cost	Single		
Younger	Dominant	739 (192)	774 (200)	35 (66)	808 (237)		
	Nondominant	762 (231)	765 (189)	2 (65)	827 (241)		
Older	Dominant	809 (180)	870 (231)	61 (75)	869 (239)		
	Nondominant	871 (249)	893 (237)	21 (98)	959 (294)		

3b. Errors		Mixed-Blocks List A			Mixed Blocks - List B		
Group	Language	Stay	Switch	Switch Cost	Stay	Switch	Switch Cost
Younger	Dominant	0.02 (0.14)	0.05 (0.21)	0.03 (0.04)	0.01 (0.09)	0.04 (0.20)	0.03 (0.06)
	Nondominant	0.02 (0.15)	0.05 (0.22)	0.03 (0.03)	0.03 (0.17)	0.06 (0.24)	0.03 (0.05)
Older	Dominant	0.03 (0.17)	0.09 (0.28)	0.06 (0.05)	0.02 (0.15)	0.07 (0.25)	0.04 (0.07)
	Nondominant	0.03 (0.17)	0.08 (0.27)	0.05 (0.05)	0.03 (0.18)	0.06 (0.24)	0.03 (0.08)
		List A – First Half Only			List B		
		Single	Stay	Mix Cost	Single		
Younger	Dominant	0.01 (0.1)	0.02 (0.14)	0.01 (0.02)	0.001 (0.03)		
	Nondominant	0.03 (0.17)	0.03 (0.16)	-0.003 (0.04)	0.05 (0.22)		
Older	Dominant	0.01 (0.12)	0.03 (0.17)	0.02 (0.04)	0.01 (0.08)		
	Nondominant	0.02 (0.14)	0.03 (0.17)	0.01 (0.03)	0.02 (0.15)		

Note. Switch cost (RT switch - RT stay trials); Mix cost (RT stay – RT single trials). Due to the nature of the experimental design for List B (i.e., half as many trials as for List A), we do not report mixing costs for List B.

Table 3.4. *Results of a Linear Mixed Effects Model with Reaction Times (RTs; 4a) and Errors (4b) as the Dependent Variable for all Mixed-language Blocks* [a]

a. RTs	*B*	*SE (B)*	*df*	*t*-value	*p*-value
(Intercept)	873.2	13.5	74	64.8	<0.001
Language	-7.1	6.5	60	-1.1	0.279
Group	**123.4**	**27.1**	**75**	**4.6**	**<0.001**
Trial Type	**67**	**5.7**	**54**	**11.8**	**<0.001**
List	**27.2**	**7.7**	**29**	**3.5**	**0.001**
Language: Group	**30.9**	**12.3**	**60**	**2.5**	**0.014**
Language: Trial Type	-13.7	7	26	-2	0.061*
Group: Trial Type	**21.9**	**10.4**	**71**	**2.1**	**0.039**
Language: List	-15.9	8.4	22	-1.9	0.070*
Group: List	8	10.2	39	0.8	0.435
Trial Type: List	-3.4	8.8	21	-0.4	0.705
Language: Group: Trial Type	0.8	13.6	70	0.1	0.955
Language: Group: List	16	15.2	21	1.1	0.306
Language: Trial Type: List	8.5	13.6	21572	0.6	0.530
Group: Trial Type: List	-3.9	13.6	21562	-0.3	0.774
Language: Group: Trial Type: List	7.9	27.2	21568	0.3	0.772

b. Errors	*B*	*SE (B)*	*z*-value	*p*-value
(Intercept)	-3.7	0.1	-33.5	<0.001
Language	0.1	0.2	0.7	0.470
Group	**0.5**	**0.2**	**2.2**	**0.030**
Trial Type	**1.1**	**0.1**	**11.9**	**<0.001**
List	-0.3	0.1	-1.9	0.059*
Language: Group	-0.2	0.3	-0.8	0.415
Language: Trial Type	-0.2	0.2	-1.5	0.136
Group: Trial Type	0.1	0.2	0.8	0.410
Language: List	0.5	0.3	1.8	0.074*
Group: List	0	0.2	-0.1	0.917
Trial Type: List	0	0.2	0.1	0.951
Language: Group: Trial Type	0	0.3	0	0.961
Language: Group: List	-0.7	0.5	-1.3	0.180
Language: Trial Type: List	-0.5	0.4	-1.5	0.127
Group: Trial Type: List	-0.6	0.4	-1.8	0.077*

Note. Effects that are significant at $p < 0.05$ are bolded and marginally significant effects are marked with an asterisk.

[a] *Controlling for baseline slowing in older bilinguals.* Having found significant effects of age-related slowing, following the latest recommendations in aging research (Hedge, Powell, & Sumner, 2018; see also Faust, 1999), we converted raw RTs to z-scores separately for each individual based on their means and standard deviations across all conditions and re-ran the same four-way model for mixed-language blocks. This model revealed essentially the same results—significant main effects of Trial Type (B = 0.31; $SE(B)$ = 0.02; p <.002), List (B = 0.13; $SE(B)$ = 0.03; p <.001), and a Language X Group interaction (B =0.16; $SE(B)$ = 0.06; p = 0.01). However, the Language X List interaction became marginally significant (B = -0.07; $SE(B)$ = 0.04; p = 0.06.

Table 3.5. *Results of a Linear Mixed Effects Model for all List A items with Trial Number as a Factor to Index Repetition Effects*

	B	*SE (B)*	df	*t*-value	*p*-value
Intercept	865.2	13.6	74.2	63.6	<0.001
Language	-2.8	6.3	53.9	-0.4	0.656
Group	**120.2**	**27.3**	**74.9**	**4.4**	**<0.001**
Trial Number	5.9	3.7	62.8	1.6	0.114
Language: Group	**27.6**	**12.5**	**53.2**	**2.2**	**0.031**
Language: Trial Number	-6.1	3.8	22.8	-1.6	0.121
Group: Trial Number	-6.5	7	70.5	-0.9	0.358
Language: Group: Trial Number	-8.9	7	21.4	-1.3	0.217

Note. Effects that are significant at $p < 0.05$ are bolded.

Appendix

Mixing costs

Our focus in the present study was on mixed-language blocks, and our ability to examine mixing-costs was more limited given that we did not include a full sandwich design for list B items. However, for completion we examined mixing costs for List A items (for which we had 40 single-language trials both before and after the mixed-language blocks). An age-related increase in mix costs in language switching was previously reported in Weissberger et al., and in de Bruin et al., 2020, and is commonly reported in studies of monolingual aging effects on task-switching (Wasylyshyn et al., 2011). We conducted a Language × Group × Trial Type (single-language trials vs mixed-language stay trials) analysis separately for RTs and errors for List A items in the first half of the experiment (i.e., before intermixing List A items with List B items). Model output for these analyses are shown in the Appendix (Table A). Overall bilinguals named pictures more quickly on single-language trials than stay trials, showing mixing costs (significant main effect of Trial Type; M = 808 vs 781; SD = 216 vs 219). Mixing costs were bigger for the dominant than the non-dominant language (i.e., a mixing cost asymmetry in RTs)—a significant interaction between Language × Trial Type. Planned contrasts collapsing across Group revealed a 44 ms mixing cost for dominant language responses ($p < .001$) versus only a 9 ms mixing cost for nondominant language responses ($p = 0.21$).

A matching error analysis also revealed significant mixing costs in errors and higher mixing costs in the dominant than in the nondominant language— (i.e., a mix cost asymmetry in errors shown by a significant interaction between Language × Trial Type). Follow-up comparisons collapsed across Group revealed a significant mixing cost in errors in the dominant (M = 0.01; $p < 0.01$) but not in the nondominant language (M = 0.001; $p = 0.52$). Although the three-way interactions were not significant, we examined whether both older and younger bilinguals showed a mix cost asymmetry using planned interaction contrasts. In reaction times, both groups showed a significant switch cost asymmetry (ps = 0.002 and 0.006, for younger and older bilinguals, respectively). However, within errors, the mix cost asymmetry was significant in younger bilinguals ($p < 0.05$) but not in older bilinguals ($p = 0.38$).

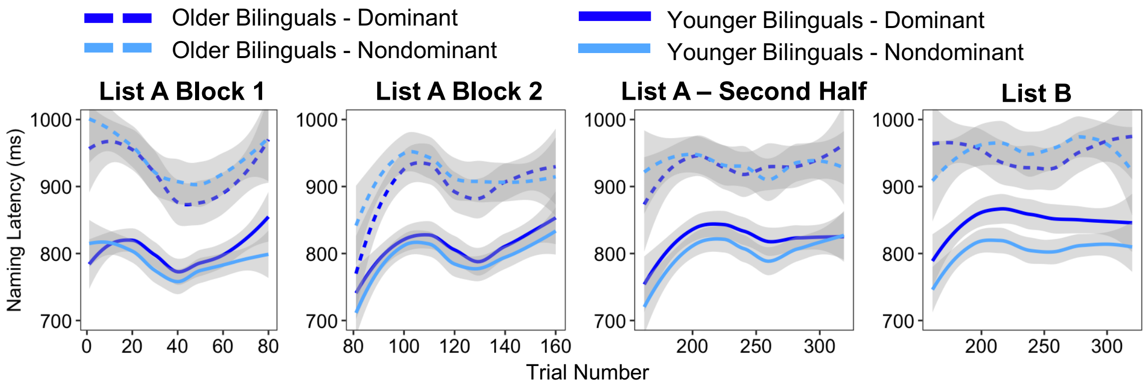
Thus, we did not replicate Weissberger et al.'s finding of larger mix costs in latencies and larger switch costs in both latencies and errors. In addition, the aging-related switching deficit appeared to be more limited in the present study as noted above (it did not survive control for slowing, and was present only in RTs not in errors). A critical difference between studies may have been that we allowed participants 33% more time to respond. We allowed participants 3 seconds to respond whereas in Weissberger et al. the response deadline was 2 seconds, which elicited substantially higher error rates and many significant effects, whereas in our study analyses of error rates appeared to exhibit floor effects (few significant effects). In Weissberger et al.'s half of the participants also completed a color-shape switching task prior to the language switching task, which could have affected subsequent language switching performance. However, at least two other studies also failed to observe an age-related increase in switch costs (Calabria et al., 2015; Hernandez & Kohnert, 2015) and mixing costs (Calabria et al., 2015).

Appendix Table A. *Results of Mixed Effects Analyses for Reaction Times (RTs) and Errors that examined Mixing Costs for List A items in the First Half of the Experiment*

RTs	*B*	*SE (B)*	*df*	*t*-value	*p*-value
(Intercept)	810.6	10	76.7	80.8	<0.001
Language	**25.1**	**8.6**	**63.4**	**2.9**	**0.005**
Trial Type	**30**	**8.3**	**62.5**	**3.6**	**0.001**
Group	**100.6**	**19.9**	**75.2**	**5**	**<0.001**
Language: Trial Type	**-36.3**	**8.7**	**70.6**	**-4.2**	**<0.001**
Language: Group	32.4	17.3	63.8	1.9	0.065*
Trial Type: Group	22.2	15.9	71	1.4	0.168
Language: Trial Type: Group	-7.1	17.5	70.6	-0.4	0.687
Errors	*B*	*SE (B)*	z	*p*-value	
(Intercept)	-4.8	0.2	-24.4	<0.001	
Language	0.5	0.3	1.4	0.154	
Trial Type	**0.5**	**0.2**	**2.7**	**0.008**	
Group	0.1	0.4	0.2	0.870	
Language: Trial Type	**-0.6**	**0.3**	**-2.1**	**0.036**	
Language: Group	-0.4	0.7	-0.6	0.525	
Trial Type: Group	0.4	0.3	1.0	0.295	
Language: Trial Type: Group	0.4	0.6	0.7	0.479	

Note. Effects that are significant at $p < 0.05$ are bolded and marginally significant effects ($p < 0.10$) are depicted with an asterisk.

Appendix Figure A. *Naming Latencies (Collapsed Across Stay and Switch Trials) as a Function of Trial Number Plotted Separately by Mixed-Language Block*



Note. Blocks 1 and 2 contain 80 trials *each* whereas List A- Second Half and List B contain 160 trials each. Although a linear effect of trial number was entered into the mixed effects model, for visualization, trial-level RTs are LOESS-smoothed (i.e., local regression), which is represented by the 95% confidence interval ribbons.

References

Amer, T., Campbell, K. L., & Hasher, L. (2016). Cognitive control as a double-edged sword. *Trends in Cognitive Sciences*, *20*(12), 905–915. https://doi.org/10.1016/j.tics.2016.10.002

Amer, T., & Hasher, L. (2014). Conceptual processing of distractors by older but not younger adults. *Psychological Science*, *25*(12), 2252–2258. https://doi.org/10.1177/0956797614555725

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390–412. https://doi.org/10.1016/j.jml.2007.12.005

Bates, D., Kliegl, R., Vasishth, S., & Baayen, H. (2018). Parsimonious mixed models. *ArXiv.1506.04967 [Stat]*. http://arxiv.org/abs/1506.04967

Bobb, S. C., & Wodniecka, Z. (2013). Language switching in picture naming. What asymmetric switch costs (do not) tell us about inhibition in bilingual speech planning. *Journal of Cognitive Psychology*, *25*(5), 568–585. https://doi.org/10.1080/20445911.2013.792822

Branzi, F. M., Martin, C. D., Abutalebi, J., & Costa, A. (2014). The after-effects of bilingual language production. *Neuropsychologia*, *52*, 102–11

Braver, T.S. (2012). The variable nature of cognitive control. A dual mechanisms framework. *Trends in Cognitive Sciences*, *16*(2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., Janowsky, J. S., Taylor, S. F., Yesavage, J. A., Mumenthaler, M. S., Jagust, W. J., & Reed, B. R. (2001). Context processing in older adults. Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology. General*, *130*(4), 746–763.

Braver T.S, Gray J.R, Burgess G.C. Explaining the many varieties of working memory variation. Dual mechanisms of cognitive control. In. Conway A, et al., editors. Variation in Working Memory. Oxford University Press; Oxford. 2007. pp. 76–106.

Braver, T.S., Satpute, A. B., Rush, B. K., Racine, C. A., & Barch, D. M. (2005). Context processing and context maintenance in healthy aging and early stage dementia of the Alzheimer's type. *Psychology and Aging*, *20*(1), 33–46. https://doi.org/10.1037/0882-7974.20.1.33

Brown, R., & McNeill, D. (1966). The "tip of the tongue" phenomenon. *Journal of Verbal Learning & Verbal Behavior, 5(*4), 325–337. https://doi.org/10.1016/S0022-5371(66)80040-3

Brown AS, Nix LA. (1996). Age-related changes in the tip-of-the-tongue experience. *American Journal of Psychology*, *109,* 79–91. doi. 10.2307/1422928.

Bugg, J. M. (2014). Evidence for the sparing of reactive cognitive control with age. *Psychology and Aging*, *29*(1), 115–127. https://doi.org/10.1037/a0035270

Burke, D. M. (1997). Language, aging, inhibitory deficits. Evaluation of a theory. *Journal of Gerontology, 52B*, 254–264.

Burke, D. M., Locantore, J. K., Austin, A. A., & Chae, B. (2004). Cherry pit primes Brad Pitt.

Homophone priming effects on young and older adults' production of proper names. *Psychological Science*, *15*(3), 164–170. https://doi.org/10.1111/j.0956-7976.2004.01503004.x

Burke D.M, MacKay D.G, Worthley J.S, Wade E. (1991). On the tip of the tongue. What causes word finding failures in young and older adults? *Journal of Memory and Language*, *30*, 542–579.

Burke, D. M., & Osborne, G. L. (2007). Aging and inhibition deficits. Where are the effects? In D. Gorfein & C. MacLeod (Eds.), On the place of inhibitory processes in cognition. Washington, DC. American Psychological Association Press.

Bialystok, E. (2017). The bilingual adaptation. How minds accommodate experience. *Psychological Bulletin*, *143*(3), 233–262. https://doi.org/10.1037/bul0000099

Calabria, M., Branzi, F. M., Marne, P., Hernández, M., & Costa, A. (2015). Age-related effects over bilingual language control and executive control. *Bilingualism. Language and Cognition*, *18*(1), 65–78. https://doi.org/10.1017/S1366728913000138

Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control. An event-related brain potential study. *Brain Research*, *1147*, 192-208.

Christoffels I., Ganushchak L. & La Heij W. (2016), When L1 suffers. Sustained, global slowing and the reversed language effect in mixed language context. In. Schwieter J.W. (Ed.) Cognitive control and consequences of multilingualism. Amsterdam. John Benjamins Publishing Company (pp. 171-192).

Cohen, J. D., Barch, D. M., Carter, C., & Servan-Schreiber, D. (1999). Context-processing deficits in schizophrenia. Converging evidence from three theoretically motivated cognitive tasks. *Journal of Abnormal Psychology*, *108*(1), 120–133. https://doi.org/10.1037/0021-843X.108.1.120

Costa, A., & Santesteban, M. (2004). Lexical access in bilingual speech production. Evidence from language switching in highly proficient bilinguals and L2 learners. *Journal of Memory and Language*, *50*(4), 491–511. https://doi.org/10.1016/j.jml.2004.02.002

Costa, A., Santesteban, M., & Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *32*(5), 1057–1074. https://doi.org/10.1037/0278-7393.32.5.1057

Cross ES, Burke DM. (2004). Do alternative names block young and older adults' retrieval of proper names? *Brain and Language, 89*,174–181.

de Bruin, A., Samuel, A. G., & Duñabeitia, J. A. (2020). Examining bilingual language switching across the lifespan in cued and voluntary switching contexts. *Journal of Experimental Psychology. Human Perception and Performance*. https://doi.org/10.1037/xhp0000746

Declerck, M. (2020). What about proactive language control? *Psychonomic Bulletin & Review*, *27*(1), 24–35. https://doi.org/10.3758/s13423-019-01654-1

Decklerck, M., Kleinman, D., Gollan, T.H (submitted). Which bilinguals reverse language dominance and why?

Declerck, M., Koch, I., & Philipp, A. M. (2012). Digits vs. pictures. The influence of stimulus type on language switching*. *Bilingualism. Language and Cognition*, *15*(4), 896–904. https://doi.org/10.1017/S1366728912000193

Declerck, M., & Philipp, A. M. (2015). A review of control processes and their locus in language switching. *Psychonomic Bulletin & Review*, *22*(6), 1630–1645. https://doi.org/10.3758/s13423-015-0836-1

Dunlosky, J., & Hertzog, C. (2001). Measuring strategy production during associative learning. The relative utility of concurrent versus retrospective reports. *Memory & Cognition*, *29*(2), 247–253. https://doi.org/10.3758/BF03194918

Francis, W. S., Augustini, B. K., & Sáenz, S. P. (2003). Repetition priming in picture naming and translation depends on shared processes and their difficulty. Evidence from Spanish-English bilinguals. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *29*(6), 1283–1297. https://doi.org/10.1037/0278-7393.29.6.1283

Gollan, T. H., & Brown, A. S. (2006). From tip-of-the-tongue (TOT) data to theoretical implications in two steps. When more TOTs means better retrieval. *Journal of Experimental Psychology. General*, *135*(3), 462–483. https://doi.org/10.1037/0096-3445.135.3.462

Gollan, T. H., & Ferreira, V. S. (2009). Should I stay or should I switch? A cost–benefit analysis of voluntary language switching in young and aging bilinguals. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(3), 640–665. https://doi.org/10.1037/a0014981

Gollan, T. H., & Goldrick, M. (2016). Grammatical constraints on language switching. Language control is not just executive control. *Journal of Memory and Language*, *90*, 177–199. https://doi.org/10.1016/j.jml.2016.04.002

Gollan, T. H., & Goldrick, M. (2018). A switch is not a switch. Syntactically-driven bilingual language control. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *44*(1), 143–156. https://doi.org/10.1037/xlm0000462

Gollan, T. H., & Goldrick, M. (2019). Aging deficits in naturalistic speech production and monitoring revealed through reading aloud. *Psychology and Aging*, *34*(1), 25–42. https://doi.org/10.1037/pag0000296

Gollan, T. H., Kleinman, D., & Wierenga, C. E. (2014). What's easier. Doing what you want, or being told what to do? Cued versus voluntary language and task switching. *Journal of Experimental Psychology. General*, *143*(6), 2167–2195. https://doi.org/10.1037/a0038006

Gollan, T. H., Li, C., Stasenko, A., & Salmon, D. P. (2020). Intact reversed language-dominance but exaggerated cognate effects in reading aloud of language switches in bilingual Alzheimer's disease. *Neuropsychology*, *34*(1), 88–106. https://doi.org/10.1037/neu0000592

Gollan, T. H., Sandoval, T. C., & Salmon, D. P. (2011). Cross-language intrusion errors in aging bilinguals reveal the link between executive control and language selection. *Psychological Science*. https://doi.org/10.1177/0956797611417002

Gollan, T. H., Schotter, E. R., Gomez, J., Murillo, M., & Rayner, K. (2014). Multiple levels of bilingual language control. Evidence from language intrusions in reading aloud. *Psychological Science*, *25*(2), 585–595. https://doi.org/10.1177/0956797613512661

Gollan, T. H., Stasenko, A., Li, C., & Salmon, D. P. (2017). Bilingual language intrusions and other speech errors in Alzheimer's disease. *Brain and Cognition*, *118*, 27–44. https://doi.org/10.1016/j.bandc.2017.07.007

Gollan, T. H., Weissberger, G. H., Runnqvist, E., Montoya, R. I., & Cera, C. M. (2012). Self-ratings of Spoken Language Dominance. A Multi-Lingual Naming Test (MINT) and preliminary norms for young and aging Spanish-English bilinguals. *Bilingualism (Cambridge, England)*, *15*(3), 594–615. https://doi.org/10.1017/S1366728911000332

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism, Language and Cognition, 1*, 67–81.

Hanulová, J., Davidson, D. J., & Indefrey, P. (2011). Where does the delay in L2 picture naming come from? Psycholinguistic and neurocognitive evidence on second language word production. *Language and Cognitive Processes*, *26*(7), 902–934. https://doi.org/10.1080/01690965.2010.509946

Hasher, L. (2015). Inhibitory Deficit Hypothesis. In The Encyclopedia of Adulthood and Aging (pp. 1–5). https://doi.org/10.1002/9781118521373.wbeaa259

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging. A review and a new view. In *The psychology of learning and motivation. Advances in research and theory, Vol. 22* (pp. 193–225). Academic Press. https://doi.org/10.1016/S0079-7421(08)60041-9

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), Attention and performance. Attention and performance XVII. Cognitive regulation of performance. Interaction of theory and application (p. 653–675). The MIT Press.

Heikoop, K. W., Declerck, M., Los, S. A., & Koch, I. (2016). Dissociating language-switch costs from cue-switch costs in bilingual language switching. *Bilingualism. Language and Cognition*, *19*(5), 921–927. https://doi.org/10.1017/S1366728916000456

Hernandez, A. E., & Kohnert, K. J. (1999). Aging and language switching in bilinguals. *Aging, Neuropsychology, and Cognition*, *6*(2), 69–83. https://doi.org/10.1076/anec.6.2.69.783

Hernandez, A. E., & Kohnert, K. J. (2015). Investigations into the locus of language-switching costs in older adult bilinguals. *Bilingualism. Language and Cognition*, *18*(1), 51–64. https://doi.org/10.1017/S136672891300045X

Hoaglin, D. C., & Iglewicz, B. (1987). Fine-tuning some resistant rules for outlier labeling. *Journal of the American Statistical Association*, *82*(400), 1147–1149.

Hoaglin, D, Iglewicz, B & Tukey, J. (1986) Performance of some resistant rules for outlier labeling. *Journal of the American Statistical Association, 81,* 991-999.

Ivanova, I., Murillo, M., Montoya, R. I., & Gollan, T. H. (2016). Does bilingual language control decline in older age? *Linguistic Approaches to Bilingualism*, *6*(1–2), 86–118.

https://doi.org/10.1075/lab.15003.iva

Jacoby, L. L., Lindsay, D. S., & Hessels, S. (2003). Item-specific control of automatic processes. Stroop process dissociations. *Psychonomic Bulletin & Review*, *10*(3), 638–644. https://doi.org/10.3758/bf03196526

Jylkkä, J., Lehtonen, M., Lindholm, F., Kuusakoski, A., & Laine, M. (2018). The relationship between general executive functions and bilingual switching and monitoring in language production. *Bilingualism. Language and Cognition*, *21*(3), 505–522. https://doi.org/10.1017/S1366728917000104

Kane, M. J., May, C. P., Hasher, L., Rahhal, T., & Stoltzfus, E. R. (1997). Dual mechanisms of negative priming. *Journal of Experimental Psychology. Human Perception and Performance*, *23*(3), 632–650. https://doi.org/10.1037//0096-1523.23.3.632

Kavé, G., & Goral, M. (2017). Do age-related word retrieval difficulties appear (or disappear) in connected speech? *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition*, *24*(5), 508–527. https://doi.org/10.1080/13825585.2016.1226249

Kemper, S., Kynette, D., Rash, S., O'Brien, K., & Sprott, R. (1989). Life-span changes to adults' language. Effects of memory and genre. *Applied Psycholinguistics*, *10*(1), 49–66. https://doi.org/10.1017/S0142716400008419

Khateb, A., Shamshoum, R., & Prior, A. (2017). Modulation of language switching by cue timing. Implications for models of bilingual language control. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *43*(8), 1239–1253. https://doi.org/10.1037/xlm0000382

Kleinman, D., & Gollan, T. H. (2016). Speaking two languages for the price of one. bypassing language control mechanisms via accessibility-driven switches. *Psychological Science*, *27*(5), 700–714. https://doi.org/10.1177/0956797616634633

Kleinman, D., & Gollan, T. H. (2018). Inhibition accumulates over time at multiple processing levels in bilingual language control. *Cognition*, *173*, 115–132. https://doi.org/10.1016/j.cognition.2018.01.009

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching. A review. *Psychonomic Bulletin & Review*, *17*(1), 1–14. https://doi.org/10.3758/PBR.17.1.1

Kolers, P. A. (1966). Reading and talking bilingually. *The American Journal of Psychology*, *79*(3), 357–376. https://doi.org/10.2307/1420877

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging*, *15*(1), 126–147. https://doi.org/10.1037//0882-7974.15.1.126

Kreiner, H., & Degani, T. (2015). Tip-of-the-tongue in a second language. The effects of brief first-language exposure and long-term use. *Cognition*, *137*, 106–114. https://doi.org/10.1016/j.cognition.2014.12.011

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package. Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(1), 1–26.

https://doi.org/10.18637/jss.v082.i13

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. P*sychological Bulletin, 144*, 394–425.

MacLeod, C. M., Dodd, M. D., Sheard, E. D., Wilson, D. E., & Bibi, U. (2003). In opposition to inhibition. In Psychology Of Learning And Motivation - Advances In Research And Theory (Vol. 43, pp. 163-214).

Maylor, E. A. (1990). Age, blocking and the tip of the tongue state. *British Journal of Psychology*, *81*(2), 123–134. https://doi.org/10.1111/j.2044-8295.1990.tb02350.x

Meiran, N., and Gotler, A. (2001). Modelling cognitive control in task switching and aging. *Eur. J. Cogn. Psychol*. *13*, 165–186. doi. 10.1080/09541440042000269

Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming. Asymmetrical costs of language selection. *Journal of Memory and Language*, *40*(1), 25–40. https://doi.org/10.1006/jmla.1998.2602

Misra, M., Guo, T., Bobb, S. C., & Kroll, J. F. (2012). When bilinguals choose a single word to speak. Electrophysiological evidence for inhibition of the native language. *Journal of Memory and Language*, *67*(1). https://doi.org/10.1016/j.jml.2012.05.001

Ramscar, M., Hendrix, P., Shaoul, C., Milin, P., & Baayen, H. (2014a). The myth of cognitive decline. Non-linear dynamics of lifelong learning. *Topics in Cognitive Science*, *6*(1), 5–42. https://doi.org/10.1111/tops.12078

Paap, K.R., Myuz, H. Anders, R.T., Bockelman, M., Mikulinsky, R & Sawi, O.M. (2017). No compelling evidence for a bilingual advantage in switching or that frequent language switching reduces switch cost. *Journal of Cognitive Psychology, 29*, 89-112.

Peirce, J.W. (2007). PsychoPy - Psychophysics software in Python. *Journal of Neuroscience Methods, 162*, 8-13.

Pierce, J.W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics, 2*, 1-8.

Posner, M.I. Snyder CR. Facilitation and inhibition in the processing of signals. In. Rabbitt PM, Dornic S, editors. Attention and Performance. Vol. 5. San Diego, CA. Academic Press; 1975. pp. 669–682.

Prior, A., & Gollan, T. (2011). Good language switchers are good task switchers. Evidence from Spanish English and Mandarin-English bilinguals. *Journal of the International Neuropsychological Society, 17*, 682-691. doi.10.1017/S1355617711000580

R Core Team (2017). R. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https.//www.R-project.org/.

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., Dahle, C., Gerstorf, D., & Acker, J. D. (2005). Regional brain changes in aging healthy adults. General trends, individual differences and modifiers. *Cerebral Cortex (New York, N.Y.. 1991)*, *15*(11), 1676–1689.https://doi.org/10.1093/cercor/bhi044

Rey-Mermet, A., & Gade, M. (2018). Inhibition in aging. What is preserved? What declines? A meta-analysis. *Psychonomic Bulletin & Review*, *25*(5), 1695–1716. https://doi.org/10.3758/s13423-017-1384-7

Rey-Mermet, A., Gade, M., & Oberauer, K. (2018). Should we stop thinking about inhibition? Searching for individual and age differences in inhibition ability. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *44*(4), 501–526. https://doi.org/10.1037/xlm0000450

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *31*(6), 1477–1491. https://doi.org/10.1037/0278-7393.31.6.1477

Salthouse, T. A. (2010). Is flanker-based inhibition related to age? Identifying specific influences of individual differences on neurocognitive variables. *Brain and Cognition*, *73*(1), 51–61. https://doi.org/10.1016/j.bandc.2010.02.003

Shafto, M. A., & Tyler, L. K. (2014). Language in the aging brain. The network dynamics of cognitive decline and preservation. *Science (New York, N.Y.)*, *346*(6209), 583–587. https://doi.org/10.1126/science.1254404

Stasenko, A., & Gollan, T. H. (2019). Tip of the tongue after any language. Reintroducing the notion of blocked retrieval. *Cognition*, *193*, 104027. https://doi.org/10.1016/j.cognition.2019.104027

Sullivan, M. P., & Faust, M. E. (1993). Evidence for identity inhibition during selective attention in old adults. *Psychology and Aging*, *8*(4), 589–598. https://doi.org/10.1037//0882-7974.8.4.589

Tamnes, C. K., Walhovd, K. B., Dale, A. M., Østby, Y., Grydeland, H., Richardson, G., Westlye, L. T., Roddey, J. C., Hagler, D. J., Due-Tønnessen, P., Holland, D., Fjell, A. M., & Alzheimer's Disease Neuroimaging Initiative. (2013). Brain development and aging. Overlapping and unique patterns of change. *NeuroImage*, *68*, 63–74. https://doi.org/10.1016/j.neuroimage.2012.11.039

Taylor, J. K., & Burke, D. M. (2002). Asymmetric aging effects on semantic and phonological processes. Naming in the picture-word interference task. *Psychology and Aging, 17*(4), 662–676. https://doi.org/10.1037/0882-7974.17.4.662

Van Assche, E., Duyck, W., & Gollan, T. H. (2013). Whole-language and item-specific control in bilingual language production. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *39*(6), 1781–1792. https://doi.org/10.1037/a0032859

Verhaeghen, P. (2003). Aging and vocabulary scores. A meta-analysis. *Psychology and Aging*, *18*(2), 332–339. https://doi.org/10.1037/0882-7974.18.2.332

Verhaeghen, P. (2011). Aging and executive control. Reports of a demise greatly exaggerated. *Current Directions in Psychological Science*, *20*(3), 174–180. https://doi.org/10.1177/0963721411408772

Verhoef, K. M. W., Roelofs, A., & Chwilla, D. J. (2010). Electrophysiological evidence for endogenous control of attention in switching between languages in overt picture naming. *Journal of Cognitive Neuroscience*, *22*(8), 1832–1843. https://doi.org/10.1162/jocn.2009.21291

Verhoef, K., Roelofs, A., & Chwilla, D. J. (2009). Role of inhibition in language switching. Evidence from event-related brain potentials in overt picture naming. *Cognition*, *110*(1), 84–99. https://doi.org/10.1016/j.cognition.2008.10.013

Wardlow, L., Ivanova, I., & Gollan, T. H. (2014). The cognitive mechanisms underlying perspective taking between conversational partners. Evidence from speakers with Alzheimer's disease. *Neuropsychologia*, *56*, 184–195. https://doi.org/10.1016/j.neuropsychologia.2014.01.013

Wasylyshyn, C., Verhaeghen, P., & Sliwinski, M. J. (2011). Aging and task switching. A meta-analysis. *Psychology and Aging*, *26*(1), 15–20. https://doi.org/10.1037/a0020912

Weissberger, G. H., Wierenga, C. E., Bondi, M. W., & Gollan, T. H. (2012). Partially overlapping mechanisms of language and task control in young and older bilinguals. *Psychology and Aging*, *27*(4), 959–974. https://doi.org/10.1037/a0028281

Wodniecka, Z., Szewczyk, J., Kałamała, P., Mandera, P., & Durlik, J. (2020). When a second language hits a native language. What ERPs (do and do not) tell us about language retrieval difficulty in bilingual language production. *Neuropsychologia*, *141*, 107390. https://doi.org/10.1016/j.neuropsychologia.2020.107390

Wu, Y. J., & Thierry, G. (2010). Chinese-English bilinguals reading English hear Chinese. The *Journal of Neuroscience, 30*, 7646–7651. http://dx.doi.org/10.1523/JNEUROSCI.1602-10.2010

Xiang, L., Zhang, B., Wang, B., Jiang, J., Zhang, F., & Hu, Z. (2016). The effect of aging on the dynamics of reactive and proactive cognitive control of response interference. *Frontiers in Psychology*, *7.*

Zacks, R. T., & Hasher, L. (1994). Directed ignoring. Inhibitory regulation of working memory. In D. Dagenbach & T. H. Carr (Eds.), Inhibitory processes in attention, memory, and language (p. 241–264). Academic Press.

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CONCLUSION OF THE DISSERTATION

Three studies explored the intersection between bilingual language control and executive control with behavioral and neuroimaging methods. In Chapter 1, we tested a possible bilingual advantage in task switching, finding that bilinguals demonstrated smaller costs of switching with a longer preparation time and within the first half of the experiment, suggesting that bilinguals' switching advantage may be more related to preparing to switch than to switching per se, which could represent better proactive control. In Chapter 2, we investigated whether domain-general executive control regions are recruited in bilingual switching during comprehension using a silent reading task, revealing that fronto-parietal cognitive control areas were activated when bilinguals read paragraphs that required switching between languages. These results considerably broaden the range of switching tasks that have previously been shown to engage the language control network and demonstrate their involvement in comprehension (not just in production). Finally, in Chapter 3, we examined whether aging bilinguals will exhibit reversal of language dominance and if this reversal would transfer across different sets of stimulus items to probe whether language control operates on a global level. We found that only younger, but not older bilinguals, demonstrated reversed language dominance, and transfer across item sets was also limited to younger bilinguals. These findings suggest language control arises primarily at the whole-language (global) level and is shared with domain-general proactive control and therefore impaired in aging.

Study 1 revealed how limited the bilingual advantage in switching was and demonstrated low correlations between linguistic and non-linguistic switch costs (see also Segal, Stasenko, & Gollan, 2019 for evidence showing that different measures of switching vary in the extent to which they measure actual switching ability). Difference scores have also been criticized for having low reliability (Draiheim et al., 2019; see also Hilchey & Klein, 2011). Taken together, correlational evidence will always be limited, and this may be part of the reason the bilingual advantage has been elusive (e.g., Bialystok, 2017 for review). We sought to improve upon this in Studies 2 and 3, in which instead of focusing on correlations and comparing bilinguals to monolinguals, we examined the nature of bilingual language control within bilinguals, relying on experimental manipulations to better reveal the nature of bilingual language control itself, leading to a sharper understanding of how bilinguals manage dual-language activation. We concluded that cognitive control is recruited even in seemingly passive comprehension during switching, and proactive inhibition of the dominant language may help bilinguals efficiently switch languages. In Study 3, we isolated inhibition at different processing levels—that is, local and global inhibition within the language system—and made an explicit link to aging literature that used non-linguistic tasks to examine impairments in proactive versus reactive control. Broadly this suggests that the most fruitful approach going forward is to specify in greater detail the language processing dynamics *within* bilinguals, which must precede attempts to figure out how bilingual language control might be related to broader executive functions. For example, although it has been proposed that inhibition is not the component of executive functions that shows the bilingual advantage (e.g., Bialystok, 2017; Hilchey & Klein, 2011), inhibition is clearly important in bilingual language processing and additional work is needed to investigate different forms of inhibition within the language system. With a better eventual understanding of the different levels of bilingual language control, we may benefit from including additional manipulations that could interleave cognitive control tasks with language-specific tasks to see how one may influence the other (e.g., Adler et al., 2020) and evaluate whether aging bilinguals can be trained to apply proactive control (e.g., Paxton et al., 2006). Our ultimate goal should be to better understand how the concept of cognitive inhibition is related to what bilinguals do in their daily naturalistic language use.

Taken together, these studies add to accumulating evidence that domain-general cognitive control and inhibition are important mechanisms in bilingual language control and are observed in both production and comprehension. That is, bilinguals appear to rely on cognitive control broadly and in both modalities (e.g., van Heuven & Dijkstra, 2010). A decline in language control in aging provides additional support for the coupling between language and cognitive control. Furthermore, we conclude that inhibition of the dominant language may be related to proactive control, which may be a key mechanism of bilingual language production as observed during language switching.

A broader implication from our findings is that bilingualism may be an even more intensive mental gym than proposed and may be relevant for understanding cognitive reserve and attempts to stave off cognitive decline in normal aging, sidestepping the debate on whether bilingualism entails a greater need for cognitive control than monolingualism (e.g., Lehtonen et al., 2018; Jylkkä et al., 2018). Second, the paragraphs task provides a more ecologically valid approach to studying bilingual language switching. The read-aloud version of this task continues to be evaluated as a marker to detect bilingual Alzheimer's disease (e.g., Gollan et al., 2017; 2019). Our current neural data suggest that this task—even when modified to be a silent reading comprehension task—elicits significant activation in cognitive control regions. On a broader and clinically-relevant scale, this implies that this naturalistic and untimed task may eventually serve as a useful measure of executive function in a neuropsychological battery, and with various bilingual populations outside of Alzheimer's disease who are known to display executive dysfunction (e.g., vascular and frontotemporal dementia, traumatic brain injury).

By examining bilingual language control in concert with executive function and how these processes may change in healthy aging, we not only build a more comprehensive picture of language processing but may also build the foundation for improving cognitive assessment and treatment of the increasing number of bilingual individuals across the lifespan.

REFERENCES

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S., & Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex, 22,* 2076–2086.

Abutalebi, D. J., & Green, D. W. (2008). Control mechanisms in bilingual language production. Neural evidence from language switching studies. *Language and Cognitive Processes*, 23, 557–582.

De Baene, W., Duyck, W., Brass, M., & Carreiras, M. (2015). Brain circuit for cognitive control is shared by task and language switching. *Journal of Cognitive Neuroscience, 27*, 1752–1765.

Bialystok, E. (2017). The Bilingual adaptation. How minds accommodate experience. *Psychological Bulletin*, *143*(3), 233–262. https://doi.org/10.1037/bul0000099

Blanco-Elorrieta, E., & Pylkkänen, L. (2016). Bilingual language control in perception versus action. MEG reveals comprehension control mechanisms in anterior cingulate cortex and domain-general control of production in dorsolateral prefrontal cortex. *Journal of Neuroscience, 36*, 290–301.

Calabria, M., Branzi, F. M., Marne, P., Hernández, M., & Costa, A. (2015). Age-related effects over bilingual language control and executive control. *Bilingualism. Language and Cognition*, *18*(1), 65–78. https://doi.org/10.1017/S1366728913000138

de Bruin, A., Samuel, A. G., & Duñabeitia, J. A. (2020). Examining bilingual language switching across the lifespan in cued and voluntary switching contexts. *Journal of Experimental Psychology. Human Perception and Performance*. https://doi.org/10.1037/xhp0000746

De Bruin, A., Treccani, B., & Della, Sala, S. (2015). Cognitive advantage in bilingualism. An example of publication bias? *Psychological Science, 26*, 99-107.

Declerck, M., & Philipp, A. M. (2015). A review of control processes and their locus in language switching. *Psychonomic Bulletin & Review, 22*, 1630–1645.

Dong, Y., & Li, P. (2015). The Cognitive Science of Bilingualism. *Language and Linguistics Compass*, *9*(1), 1–13. https://doi.org/10.1111/lnc3.12099

Draheim, C., Mashburn, C. A., Martin, J. D., & Engle, R. W. (2019). Reaction time in differential and developmental research. A review and commentary on the problems and alternatives. *Psychological Bulletin, 145(*5), 508–535. doi.10.1037/ bul0000192

Garbin, G., Sanjuan, A., Forn, C., Bustamante, J. C., Rodriguez-Pujadas, A., Belloch, V., Hernandez, M., Costa, A., & Avila, C. (2010). Bridging language and attention. brain basis of the impact of bilingualism on cognitive control. *NeuroImage, 53*, 1272–1278.

Guzmán-Vélez, E., & Tranel, D. (2015). Does bilingualism contribute to cognitive reserve? Cognitive and neural perspectives. *Neuropsychology*, *29*(1), 139–150. https://doi.org/10.1037/neu0000105

Gollan, T. H., & Ferreira, V. S. (2009). Should I stay or should I switch? A cost–benefit analysis of voluntary language switching in young and aging bilinguals. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(3), 640–665. https://doi.org/10.1037/a0014981

Gollan, T. H., & Goldrick, M. (2016). Grammatical constraints on language switching. Language control is not just executive control. *Journal of Memory and Language*, *90*, 177–199. https://doi.org/10.1016/j.jml.2016.04.002

Gollan, T. H., Li, C., Stasenko, A., & Salmon, D. P. (2020). Intact reversed language-dominance but exaggerated cognate effects in reading aloud of language switches in bilingual Alzheimer's disease. *Neuropsychology*, *34*(1), 88–106. https://doi.org/10.1037/neu0000592

Gollan, T. H., Stasenko, A., Li, C., & Salmon, D. P. (2017). Bilingual language intrusions and other speech errors in Alzheimer's disease. *Brain and Cognition*, *118*, 27–44. https://doi.org/10.1016/j.bandc.2017.07.007

Hernandez, A. E., & Kohnert, K. J. (2015). Investigations into the locus of language-switching costs in older adult bilinguals. *Bilingualism. Language and Cognition*, *18*(1), 51–64. https://doi.org/10.1017/S136672891300045X

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review, 18*(4), 625–658. doi.10.3758/s13423-011-0116-7

Jylkkä, J., Lehtonen, M., Lindholm, F., Kuusakoski, A., & Laine, M. (2018). The relationship between general executive functions and bilingual switching and monitoring in language production. *Bilingualism. Language and Cognition*, *21*(3), 505–522. https://doi.org/10.1017/S1366728917000104

Kleinman, D., & Gollan, T. H. (2018). Inhibition accumulates over time at multiple processing levels in bilingual language control. *Cognition, 173*, 115-132.

Kramer, A. F., Bherer, L., Colcombe, S. J., Dong, W., & Greenough, W. T. (2004). Environmental influences on cognitive and brain plasticity during aging. *The Journals of Gerontology, Series A. Biological Sciences and Medical Sciences, 59*, M940–M957. http.//dx.doi.org/10.1093/ gerona/59.9.M940

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychological Bulletin, 144,* 394–425.

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2011). Cognitive control for language switching in bilinguals. A *quantitative meta-analysis of functional neuroimaging studies.* Language and Cognitive Processes, 27, 1479–1488.

Ma, H., Hu, J., Xi, J., Shen, W., Ge, J., Geng, F., Wu, Y., Guo, J., & Yao, D. (2014). Bilingual cognitive control in language switching. An fMRI study of English-Chinese late bilinguals. *PLoS ONE, 9*, 1-8.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions. Four general conclusions. *Current Directions in Psychological Science*, *21*(1), 8–14. https://doi.org/10.1177/0963721411429458

Paap, K. R., & Sawi, O. (2014). Bilingual advantages in executive functioning. problems in convergent validity, discriminant validity, and the identification of the theoretical constructs. *Frontiers in Psychology, 5*, 1-15.

Paap, K.R., Myuz, H. Anders, R.T., Bockelman, M., Mikulinsky, R & Sawi, O.M. (2017). No compelling evidence for a bilingual advantage in switching or that frequent language switching reduces switch cost. *Journal of Cognitive Psychology, 29*, 89-112.

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., Dahle, C., Gerstorf, D., & Acker, J. D. (2005). Regional brain changes in aging healthy adults. General trends, individual differences and modifiers. *Cerebral Cortex (New York, N.Y.. 1991)*, *15*(11), 1676–1689. https.//doi.org/10.1093/cercor/bhi044

Tamnes, C. K., Walhovd, K. B., Dale, A. M., Østby, Y., Grydeland, H., Richardson, G., Westlye, L. T., Roddey, J. C., Hagler, D. J., Due-Tønnessen, P., Holland, D., Fjell, A. M., & Alzheimer's Disease Neuroimaging Initiative. (2013). Brain development and aging. Overlapping and unique patterns of change. *NeuroImage*, *68*, 63–74. https.//doi.org/10.1016/j.neuroimage.2012.11.039

Weissberger, G. H., Gollan, T. H., Bondi, M. W., Clark, L. R., & Wierenga, C. E. (2015). Language and task switching in the bilingual brain. Bilinguals are staying, not switching, experts. *Neuropsychologia, 66*, 193–203.

Weissberger, G. H., Wierenga, C. E., Bondi, M. W., & Gollan, T. H. (2012). Partially overlapping mechanisms of language and task control in young and older bilinguals. *Psychology and Aging*, *27*(4), 959–974. https.//doi.org/10.1037/a0028281

Yehene, E., & Meiran, N. (2007). Is there a general task switching ability? *Acta Psychologica*, *126*(3), 169–195. https.//doi.org/10.1016/j.actpsy.2006.11.007

Zacks, R. T., & Hasher, L. (1994). Directed ignoring. Inhibitory regulation of working memory. In D. Dagenbach & T. H. Carr (Eds.), Inhibitory processes in attention, memory, and language (pp. 241–264). San Diego, CA. Academic Press.