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Assessing How Bilingual Experience Impacts Performance in Stimulus-Stimulus and Stimulus-Response Conflict Tasks

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ASSESSING HOW BILINGUAL EXPERIENCE IMPACTS PERFORMANCE IN STIMULUS-STIMULUS AND STIMULUS-RESPONSE CONFLICT TASKS

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ASSESSING VARIABILITY IN BILINGUAL SELECTIVE ATTENTION THROUGH STIMULUS-STIMULUS AND STIMULUS-RESPONSE CONFLICT TASKS

by

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Abstract

Numerous studies have revealed that bilingual individuals outperform monolinguals in tasks requiring executive control. However, the exact impact of bilingualism on executive functions remains unclear due to inconsistent findings in the literature. These discrepancies may stem from factors such as participant demographics, variations in definitions and operationalizations of bilingualism, and task selection. To address these issues, we investigated the link between degree of balance and contextual use with the ability to address conflict across sensory modalities (auditory and visual) at different stages of processing. Rather than focusing on mean performance, this study investigated performance stability (coefficient of variation) over time to uncover any adaptations that may occur in non-verbal selective attention and conflict resolution tasks. 120 English and Spanish bilinguals were recruited and asked to complete a Simon-type (with stimulus-response conflict) and a Stroop-type (with stimulus-stimulus conflict) task. Our results indicate that greater balance across languages is associated with more variability in task performance, especially in the auditory Stroop task, which shows strong evidence of language modulation, possibly as a result of increased task difficulty and a strain on the availability of cognitive resources due to high language control requirements. We also found that participants with more exposure to a high language control environment had higher interference scores. Our results reveal that the context in which languages are used does impact cognitive abilities, although not in the way prior studies have reported. As our findings are not entirely in accord with previous research, we offer possible explanations for these discrepancies.

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Chapter 1: Introduction

It is estimated that roughly 43% of the world's population, or approximately 3.3 billion people worldwide, can speak more than one language, (Gration, 2022). Positives outcomes include enhanced communication skills that aid cross-cultural understanding (García, 2019), increased job opportunities (Chiswick & Miller, 2014), improved academic performance (Adesope, Lavin, Thompson, & Ungerleider, 2010), greater cultural awareness (Cummins, 2009), and a sense of satisfaction that fosters personal growth (Ushioda & Dörnyei, 2011). However, recently there has been a surge of interest in how bilingualism impacts domains of cognition, including cognitive flexibility, attention, and problem-solving abilities (Bialystok, 2017).

Though some positive impacts of bilingual experience have been found for cognitive abilities (Bonfieni, Pickering, & Sorace, 2020), results are inconsistent across individuals or conditions. In addition, some argue that the extent of these benefits may depend on multiple factors, such as age of acquisition of the languages (Luk, Bialystok, Craik, & Grady, 2011), language proficiency (Luk & Bialystok, 2013), and type of task used to explore the cognitive phenomena of interest (Bialystok, Martin, Viswanathan, 2005). In addition, genetics may play a role in the expression of bilingual adaptations in cognition. For example, a study by Hernandez et al. (2015) found that individuals with a specific genetic variant associated with enhanced cognitive control showed more significant cognitive benefits of bilingual status. Other studies suggest that benefits are greater for those exposed to multiple languages from an early age (Kroll, Duassias, Bogulski, & Valdes-Kroff, 2012) and for individuals who are motivated to learn another language (Abutalebi & Green, 2016). Given the complexity of bilingual experience more systematic investigations are needed to understand how specific individual differences, including language experience and proficiency, may modulate cognitive behavior across different tasks.

1.1 The Role of Executive Functions in Bilingual Adaptations

Evidence that bilingual individuals have parallel activation of two their two languages, regardless of the language system targeted (Grainger, 1993; Kroll, Dussias, Bice, and Perrotti, 2015), has led researchers to speculate that bilingual individuals may engage executive control functions to operate in one of their two languages selectively. An early and highly influential account of how bilingual speakers select a target language and communicate in that language while making few speech errors was the Inhibitory Control (IC) model (Green, 1998). Green proposed that a supervisory attentional system receives signals from top-down cues that engage inhibitory action upon a non-target language. This allows for the proper contextual and linguistic representations to be used. This theory was well-received and was introduced around the time Miyake et al. (2000) proposed their model of executive functions (EF). In their Unitiy and Diversity Model, Miyake and colleagues defined EF as comprised of three core processes: 1) mental set shifting (**Shifting** or mental flexibility), 2) information updating and monitoring in working memory **(Updating**), and 3) inhibition of irrelevant information (**Inhibition**, which includes inhibitory control [behavioral control] and interference control [selective attention and cognitive inhibition]) (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; for a full review, see Diamond, 2013). Studies showing few intrusion errors of the non-target language by bilingual speakers were taken as evidence that inhibition is used to manage two languages (Liu et al., 2016; Misra et al., 2012). However, the concept of inhibition as a unique EF is suspect, given that tasks purporting to measure inhibition do not always correlate well (Paap & Greenberg, 2013). Miyake and colleagues later restructured the Unity & Diversity Model into the

Unity/Diversity Framework. For this framework, they proposed that each of the three executive function abilities proposed in the earlier model is comprised of both a common element across all (*unity*) (i.e., common EF) and components unique to each executive skill (*diversity*) (i.e., ability-specific EF). Interestingly, only updating and shifting uniquely accounted for variance above and beyond common EF in this new framework, while inhibition did not. The authors found that inhibition correlates very well with common EF but accounts for no unique variance. However, it is possible that the problems with the specification of inhibition as a unique construct and other factors may have led to inconsistent findings regarding the impact of bilingual experience on EF.

Beyond recognizing the problems with inhibition as the primary mechanism through which bilinguals control their languages, researchers began to understand that other factors beyond simply being bilingual might impact mechanisms of control. Green introduced the Adaptive Control Hypothesis (ACH) (Green & Abutalebi, 2013), which argues that the context in which people use their languages is as important as a person's degree or type of bilingualism (Bialystok, 2017). This framework theorizes that the manners in which bilingual speakers utilize their two languages can inflict different demands on executive function systems and related neurocircuitry (Zirnstein, van Hell, & Kroll, 2019). The ACH differentiates three main patterns of language use: single-language context (SLC), dual-language context (DLC), and dense-code switching (DCS). Bilinguals operating in SLC only speak one language in each context (e.g., one language at work and another at school), whereas bilinguals who experience DLC or DCS speak two languages in the same context (i.e., two languages at home). The main difference between these two use patterns is that DLC involves different languages spoken with different speakers (i.e., language is not mixed in the same utterance), while DCS involves code-switching, where the different languages are used in the same conversation with the same speaker. The hypothesis suggests that individuals who engage in DLC may receive the most significant benefits, as using different languages in the same situation without mixing them could require greater control and may lead to greater adaptive changes in cognitive systems. Additionally, it considers individual differences by acknowledging that adaptive changes in control processes are influenced by the unique conversational exchanges in which bilinguals engage. Therefore, it is expected that not all bilingual speakers will exhibit the same level of cognitive control benefit, which could account for the inconsistencies in findings across studies investigating bilingual control.

While a few studies have supported the ACH model (Hartano & Yang, 2016; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016), others have not. A study by Kałamała et al. (2020), for example, found no relationship between language context and efficiency of response inhibition at the behavioral level, particularly in DLC. Some researchers propose instead that executive function adaptations may be found in other aspects of cognitive control, such as attention, monitoring, and task switching, not just inhibition (Bialystok et al., 2004; Craik & Luk, 2008; Costa et al., 2008; Martin-Rhee & Bialystok, 2008). Given the issues in identifying the underlying source of cognitive adaptations, some researchers believe that assuming inhibition as the sole mechanism is inaccurate and propose hybrid accounts (Costa et al., 2006; Bialystok, 2017) under the logic that the influence of the non-target language is never absent. Given how the behavioral evidence of advantages in cognitive abilities related to the bilingual experience is less conclusive, it is no surprise that many researchers are rightly cautious about agreeing that bilingualism may affect cognition (Paap & Sawi, 2014).

1.2 Exploring the Inconsistencies

Researchers have highlighted various factors that may be responsible for inconsistent findings. For example, Morton & Harper (2007) suggested that differences in socioeconomic status (SES) might account for differences in EF attributed to bilingual experience. However, some studies on children (Engel de Abreu et al., 2012) and adults (Brito & Noble, 2018; Nair et al., 2017) where SES was controlled nonetheless report better performance by bilingual groups.

Cultural background and immigration status have also been suggested as factors that can explain bilinguals' differences in performance on tasks requiring EF. Hilchey & Klein (2011), for instance, raise the concern that the results of Bialystok et al. (2004) do not account for cultural differences that could impact the results of their study with children. Though better performance in attentional control tasks is found in children from Asian regions compared to Western countries (Yang & Yang, 2016), bilingualism is nonetheless associated with better performance above and beyond influences attributable to culture (Tran, Arredondo, & Yoshida, 2015). Furthermore, although there are claims that immigration status is concomitant with superior cognitive abilities (Fuller-Thomson, Brennenstuhl, Cooper, & Kuh, 2015), studies have shown that any differences found are not attributed to immigration history (Bialystok & Viswanathan, 2009). Overall, while there could be associations between these components and the execution of certain cognitive tasks, the studies above looking at social backgrounds are some of the few that report such factors do not play a pivotal role in the modulation of bilingual adaptations.

1.2.1 Age

A significant factor that drives the arguments for and against bilingual adaptations relates to the age of participants when exploring this phenomenon. Evidence of bilingual adaptations has been shown in children (Martin-Rhee & Bialystok, 2008; Morales, Calvo, & Bialystok, 2013; Bialystok, Martin, & Viswanathan, 2005; Poarch & Van Hell, 2012, Blom et al., 2017) in various conflict tasks, such as Flanker (Yang et al., 2011), and Simon (Martin-Rhee & Bialystok, 2008). For example, children have shown significant advantages in non-verbal tasks that require them to ignore conflicting information (Bialystok & Majumder, 1998; Mezzacappa, 2004). In other studies, however, bilingual children perform better than monolinguals in distraction avoidance but not in response inhibition, where they have to refrain from making a particular response in a task (Carlson & Meltzoff, 2008, Engel de Abreu et al., 2012, Foy & Mann, 2014). Avoiding distraction and response inhibition are not uniquely distinguishable under the Miyake et al. (2000) inhibition model, as both elements contribute equally to the inhibition component. Other results have shown that while bilingual children can ignore misleading information faster, monolingual children can acquire this same ability as they grow older (Bialystok, Martin, & Viswanathan, 2005), bringing forth the possibility that any adaptations are a temporary effect that may dissipate as we age (Bialystok et al., 2005).

Similar results have been found in adults where bilinguals show better performance in conflict tasks such as Flanker (Costa et al., 2008), theory of mind tasks (Rubio-Fernandez & Glucksberg, 2012), and Simon (Bialystok et al., 2004), including a better ability to retain instructions (Colatzo et al., 2008) and smaller task switching costs (Prior & MacWhinney, 2010). Conversely, some researchers argue that these are null findings due to minimal evidence of the association between tasks and measures assessed (Paap & Greenberg, 2013), while others find no differences in performance (Hilchey & Kelin, 2011) or may even report poorer performance for bilingual adults in tasks that required executive functions (Paap & Greenberg, 2013; Paap & Sawi, 2014; Papageorgiou, Bright, Tomas, & Filippi, 2018).

While adaptations may be more consistently found in children and older adults, these results are not commonly found in younger samples (Bialystok et al., 2012). For example, a study that examined performance on a Simon task across the lifespan found that children, middle-aged, and older adults showed bilingual adaptations in reaction time in congruent and incongruent trials but not in young adults (Bialystok et al., 2005). Likewise, when studying the Stroop effect in younger and older adults, faster reaction times were reported for both age groups relative to the monolinguals of the same age group, but this effect did not emerge for younger adults who completed a Simon arrow task (Bialystok et al., 2008). Likewise, a study that used simple and complex Simon tasks found quicker responses by older adults in the simple tasks but not for younger adults (Salvatierra & Rosselli, 2010). One explanation is that young adults are at their peak in cognitive control abilities(Bialystok & Craik, 2012). Thus, some researchers propose that bilingual adaptations for young adults may only emerge on complex tasks that require more attention (Salvatierra & Rosselli, 2010).

1.2.2 Language Operationalization

The lack of a uniform classification of bilingualism imposes a significant limitation when studying and comparing results across studies to determine how language status affects cognition. The conventional practice uses a categorical approach to compare monolinguals and bilinguals (Kremin & Byears-Heinlein, 2021). However, given language's indirect and theoretical nature, many argue that bilingualism is too complex to be determined by a simple classification (de Bruin, 2019) due to the variability among individuals and the different factors that play a role in building this variation that blur the line for comparisons (Baum & Titone, 2014). It is still possible that differences amongst dichotomized groups can still emerge and must be considered when generalizing results. For example, disparities within bilinguals include different age of acquisition, language pairs learned, or degree of proficiency across languages, whereas monolinguals may have different degree of familiarization with a second language (e.g., adults who may have taken a foreign language in school and have exposure to a second language even though they may not frequently engage in it) and would still be classified as monolinguals (Marian et al., 2007; Marian & Hayakawa, 2021).

To circumvent the issues of categorical assignments to groups, many researchers propose to model and analyze bilingualism as a continuous construct (Baum & Titone, 2014; Luk & Bialystok, 2013). In this fashion, more attributes (like those mentioned above) can be considered and captured to better represent an individual's language ability. For example, Kremin & Byers-Heinlein (2021) provide different ways to identify multilingualism, including using the traditional 2-group categorical classification of bilingualism (e.g., monolinguals or bilinguals), using more categorical groups with different sub-groups of bilinguals (e.g., monolinguals, low-proficient bilinguals, L2 learners, and high proficient bilinguals), and use of a continuous measure of bilingualism (accounting for the full spectrum of language experience and abilities; e.g., from completely monolingual [i.e., no exposure to an L2] to fully proficient bilingual [i.e., 'balanced']). Alternatively, one can take a mixed approach to consider bilingual status, where data are analyzed based on categorical membership or placement on a continuum of experience. This idea is based on the notion that variation can exist within categories (monolinguals [from no L2 to low L2 knowledge]) and bilinguals [from mid L2 to high L2 knowledge]), allowing individuals to belong to different categories to varying degrees simultaneously (Andreotti et al., 2009; Erosheva, 2005).

Amongst the different concepts of language that can be used to operationalize bilingualism, some researchers have taken the approach of using degree of balance to compare highly proficient balanced bilinguals with lower-balanced bilinguals (Weber, Johnson, Riccio, & Liew, 2016), still focusing on the degree of bilingualism instead of the presence or absence of bilingual status (Bialystok, 2007). Using this approach, some studies suggest that bilingual adaptations may be modulated by the degree of balance across an individual's two languages (Vega & Fernandez, 2011). As executive function abilities may be modulated by relative proficiency, 'unbalanced bilinguals' (i.e., individuals who are not equally proficient in their two languages) may be less likely to exhibit executive function benefits than their more 'balanced' counterparts (Vega & Fernandez, 2011). For example, a study by Carlson & Meltzoff (2008) found that native (i.e., exposed since birth) English and Spanish bilingual children performed better on a demanding task eliciting inhibition and attention than English speakers enrolled in a second language immersion program. In addition, in a study by Zied et al. (2004), balanced bilinguals performed similarly on two language versions of a Stroop task, while unbalanced bilinguals performed better only when responding in their dominant language. Finally, a study by Vega & Hernández (2011) found that more-balanced English and Spanish speakers scored lower on perseveration than less-balanced bilinguals on the Wisconsin Card Sorting Test, a task where participants must engage in efficient deployment of attention to shift cogntive strategies in response to changing demands. These results indicate that balance in language proficiency is an essential factor to consider when connecting bilingual experience to EF, with balanced bilinguals typically performing better on tasks requiring EF than their unbalanced counterparts.

As mentioned above, there are multiple options a researcher can take to classify bilingualism. Although there is some agreement that a continuous approach is more suitable for language, the categorical approach is still an option. As a result, researchers propose using the most appropriate measure that best fits the researchers' intention and ensures its use is well-justified.

1.2.3 Task Inconsistencies

In behavioral studies, the type of task used to assess bilingual effects on EF is vital to consider, particularly when identifying the mechanism responsible for these effects. However, researchers have argued that bilingual adaptations may only manifest under particular circumstances due to the problem of identifying the correct component of executive function and embedding it in a task context that consistently engages the EF of interest (a problem known as false equivalence (Bialystok & Craik, 2022). Tasks commonly used to assess attentional control include the Stroop (Bialystok, Craik, & Luk, 2008), Simon (Salvatierra & Roselli, 2011), and flanker (Bialystok, 2017). While these tasks have been traditionally linked and primarily assess inhibition, they also require individuals to manage and resolve conflicting information, suggesting involvement of attentional control mechanisms that can be deployed proactively or reactively. Thus, these tasks may be useful in investigating how bilingual experience enhances the deployment of attentional control, which aligns with recent conceptualizations of the consequences of bilingualism. The type and source of this inhibition mechanism, however, can vary from each other (Bialystok & Craik, 2022), such as when Blumenfeld & Marian (2014) found smaller Stroop than Simon effects in bilingual individuals relative to their monolingual counterparts. In the traditional Stroop task, participants are presented with two stimulus dimensions, color words (e.g., red, blue) and their color, that are either congruent (e.g., the word red printed in red font) or in conflict with one another (e.g., the word green printed in blue font). Thus, conflict or facilitation is generated among stimulus features (Stimulus-Stimulus/S-S). For example, participants are slower and less accurate when naming the font color on incongruent trials because of difficulty suppressing the prepotent tendency to read the word. In contrast, in a traditional Simon task, the conflict or facilitation occurs between the stimulus and the required response (Stimulus-Response/S-R); participants must reconcile the spatial positioning of the stimulus on a computer screen with the spatial position of the required response key (Kornblum, 1994). Some researchers believe that the different levels of monitoring that are required to manage multiple languages may be the underlying factors that drive the difference in task performance between groups, in contrast to the need to inhibit two simultaneously operating languages (Hernández, Bates, & Avila, 1996; Colomé, 2001). For instance, researchers have exposed participants to conditions that require more monitoring and switching in directional arrow Simon tasks, for which better performance in bilingual young adults has been recorded (Bialystok 2006). Similarly, Costa and colleagues (2009) found that young adult bilinguals outperformed monolinguals on a flanker task conducted under high monitoring conditions; this led them to conclude that bilinguals possess a more efficient monitoring system for conflict resolution. In a nonlinguistic Stroop task, Hernández et al. (2010) found reduced interference and enhanced facilitation in young adult bilinguals, serving as additional support for the potential adaptive effect bilingualism may have on attentional systems. Young adults, who may be at peak cognitive performance when considering their lifespan (Bialystok, Luk, & Craig, 2008; Ware, Kirkovski, & Lum, 2020), may need to be tested using more complex tasks to avoid masking any advantages in EF.

In the Blumenfeld & Marian (2014) study, Stroop-Simon differences in overall performance were observed, where bilinguals showed smaller Stroop than Simon effects compared to monolinguals, who showed less noticeable differences between both tasks. The authors concluded that Stroop mechanisms are favored over the conflict resolution mechanisms that act behind the Simon task. Differences regarding Stroop relative to Simon performance suggest that bilingualism may modulate cognitive control mechanisms that settle competition amongst two dimensions of the same stimulus. In their discussion, Blumenfeld & Marian (2014) explained that these task performance differences are driven by how language processing occurs in the bilingual mind. Bilinguals are more dependent on S-S mechanisms (which operate at the perceptual level) to resolve the cross-linguistic competition at the lexical level than S-R mechanisms (which operate at the response level). Therefore, S-S inhibition is language-internal inhibition of representations at the concept and lexical level, and S-R refers to inhibition of competing responses if two productions remain co-activated and compete for selection at the output level. While both mechanisms are involved in bilingual production, they do not occur at the same time. For instance, a bilingual person only speaking her most proficient language has resolved cross-linguistic competition (Costa & Santesteban, 2004), making the S-S mechanism involved and S-R absent. It is important to note that even though S-R inhibition may occur more often in bilinguals than monolinguals (since language switching is correlated with S-R inhibition [Linck et al., 2012]), the S-S mechanism is more common due to lexical between-language competition that occurs during comprehension and production, whereas S-R competition is limited to production (Blumenfeld & Marian 2014). Better performance in the Stroop task is also found in prior studies that report the same advantage in young adults (Costal et al., 2008; Hernandez et al., 2010; Luk et al., 2011) in both speed (Bialystok, 2006; Costa et al., 2008; Hernandez et al., 2010), and conflict resolution (Bialystok et al., 2008; Costa et al., 2008; Costal et al., 2009; Hernandez et al., 2010; Luk et al., 2011). The results of these studies suggest that tasks that elicit the use of S-S mechanism may be more likely to reveal bilingual adaptations.

1.3 Evidence of Adaptations in Neuroimaging Studies

Recently some researchers have considered the relationship between bilingual experience and neuroplasticity (Baum & Titone 2014). Namely, it is argued that rather than benefiting one specific EF process, bilingualism may lead to higher levels of cognitive flexibility (Kroll & Bialystok, 2013). Cognitive flexibility (CF) is the ability to quickly shift attentional focus to perceive, process, and respond to situations differently or shift one's behaviors when faced with a new goal (Eslinger & Grattan, 1993). It is thought to emerge from the operation of multiple cognitive processes (Ionescu, 2012), including attention shifting, conflict monitoring, and perception (Deak, 2003, p. 275). Speaking more than one language should require cognitive flexibility to continuously manage the joint activation of two languages (Marian & Spivey, 2003; Thierry & Wu, 2007). Furthermore, selecting the appropriate language and avoiding intrusions from the non-target one likely involves selective attention and goal orientation. Engagement of these mechanisms that support cognitive flexibility to control language use may also enhance the function of these mechanisms more generally during nonlinguistic tasks. Indeed, neuroscience research has found overlapping activation patterns between brain areas dedicated to language processing and those involved in cognitive control (Fedorenko & Thompson-Schill, 2014). However, the behavioral evidence for such adaptations in bilinguals is less conclusive.

For instance, researchers have found overlapping brain networks involved in language selection in bilinguals and nonverbal task switching (Abutalebi & Green, 2007). Bilingual children show greater structural density than older children and adults, reflecting physiological changes due to bilingualism (Bialystok, 2017). In adults, neuroimaging studies consistently report group differences in brain structure and function between bilinguals and monolinguals. For example, Gold et al. (2013) asked younger and older adults to perform a perceptual switching task where it was necessary to categorize stimuli while undergoing fMRI. Bilinguals in both age groups demonstrated decreased activation of the left frontal and cingulate cortices, regions responsible for language control and attention allocation, respectively. Notably, activation in this region negatively correlated with task performance, indicating that less activation was associated with better performance. However, when evidence of changes associated with bilingual experience is present in neuroimaging studies but absent in behavioral research, it leads to questions about the sensitivity of tasks and dependent measures used to detect group differences in those cases (Antoniou, 2019; Bak, 2016; Bialystok, 2016). Therefore, as noted earlier, it is worth considering the appropriateness of the tasks used, as well as other behavioral measures linked to attentional control that may be more sensitive to group differences than traditional accuracy and reaction time measures (Zhou & Krott, 2016).

One candidate is intraindividual variability (IIV), the trial-to-trial variations in behavioral performance measures such as reaction time (RT) (Bielak & Anstey, 2019). Neuroscientific studies report negative correlations between IIV and brain volume, where greater variability is associated with smaller brain volumes (Anstey et al., 2007) and poorer cognitive functioning (Bellgrove, Hester, & Garavan, 2004). Given the evidence of structural brain changes linked to bilingualism, it is worth exploring whether these may lead to lower IIV or more stable performance in attentional control tasks. Indeed, Johnson and colleagues (2015) conducted a study to measure the neural associations of IIV in a response inhibition task and concluded that greater response stability (lower IIV) was associated with more activation in the left pregenual anterior cingulate (a brain region often associated with language control [Abutalebi, Annoni, et al., 2008]). Thus, this brain region may play a role in controlling attention and efficient response selection in attentional control tasks and tasks requiring language control, paving the way for considering IIV as a sensitive behavioral measure of efficient attentional control. In addition to the link between IIV and the left cingulate cortex, other studies have explored the connection between bilingual changes and this region of the brain. A study that combined functional (event-related fMRI) and structural neuroimaging voxel-based morphometry in the dorsal anterior cingulate cortex (ACC) found that bilinguals use this area more efficiently than monolinguals to monitor nonlinguistic cognitive conflicts (Abutalebi et al., 2012). Bilinguals who adapt better to conflicting situations and outperform monolinguals show less ACC activity. This investigation also reported a positive correlation between ACC activity and local gray matter volume, suggesting the bilingual brain can better resolve cognitive conflicts in domain-general cognitive tasks. A study that used magnetoencephalography to address if ACC and the dorsolateral prefrontal cortex are the neural mechanisms underlying the ability to modulate multiple languages concluded that there is a close relationship between language control and general cognitive control in these regions (Blanco-Elorrieta & Pylkkänen, 2016). Lastly, a critical review by D'Souza and D'Souza (2016) that explored bilingual language control mechanisms in the ACC and dorsolateral prefrontal cortex concluded that the domain-general (inhibitory) control mechanism in these regions could be one of several systems that underlie bilingual adaptations.

Although IIV is typically used in neuroimaging studies, it has also been employed as a metric in behavioral research, though not extensively in bilingual research. IIV has been found to be a sensitive index in detecting early pathological processes (Anderson et al., 2016), and researchers in the aging literature commonly use this measure to evaluate progressive neurodegenerative disorders, such as Alzheimer's (Meker et al., 2021) and Parkinson's (de Frias, Dixton, & Camicioli, 2012) disease. For instance, Jackson and colleagues (2012) examined cognitively healthy older adults and those with early-stage Alzheimer's disease (AD) to perform three attention tasks (Simon, Stroop, and Consonant-Vowel Odd-Even switching task) and found that participants with early-stage AD (i.e., those with smaller cerebral white matter volume) had higher coefficient of variation (CoV) values (an emerging standard measure of inconsistency [Hultsch et al., 2000]), suggesting a significant amount of variance in their performance. Studies measuring stability performance have also revealed fluctuations in IIV in conditions that impair sustained attention, such as normal aging (Anderson et al., 2016), mild cognitive impairment (Jackson, Balota, Duchek, & Head, 2012), and traumatic brain injury (Tse, Balota, & Yap, 2010). While the intention is not to draw a direct comparison between bilingualism and aging, it is worth noting that using IIV as a measure of attentional control and stability has been established in research on age-related neurodegenerative disorders, thus ascertaining that this metric can be similarly valuable in investigating bilingual adaptations.

1.4 The Present Study

In the current study, we aim to determine how different aspects of bilingual experience (i.e., degree of balance in proficiency across two languages) and experience with using languages in different contexts impacts performance on two nonlinguistic tasks that require participants to engage in attentional control, one where conflict is experienced at the stimulus level (Stroop-type task) and one where conflict is experienced between the stimulus and response mappings (Simon-type task) across visual and auditory modalities, in a within-subjects design to enable comparisons across participants. We further examine whether bilingual experience is linked to greater performance stability in RT by examining the coefficient of variation (CoV). As IIV is a measure indicative of attentional control ability (Hultsch, MacDonald, & Dixon, 2002), we hypothesize that this measure may be susceptible to adaptations in attentional control linked to bilingual experience. In addition, language's cognitive demands may modulate IIV performance due to the increased use of executive control necessary for resolving cross-language conflict (Bialystok, Craik, & Luk, 2008). Therefore, we predict that individuals more balanced in proficiency across their two languages will show better efficiency and higher stability in performance for both nonlinguistic Simon and Stroop-type tasks, with even greater effects seen in the Stroop-type task, as has been previously found in research using similar paradigms (Blumenfeld & Marian, 2014). Further, we anticipate these effects in tasks administered in different modalities. Many past studies exploring bilingual effects on EF tasks have examined performance within a single modality (mainly visual). However, prior work has shown that bilingual adaptations may generalize across many task domains, including those involving numerical (Bialystok & Codd, 1997) and spatial (Bialystok & Majumder, 1998) concepts, conceptual classification (Bialystok, 1999), and aspects of theory of mind (Bialystok & Senman, 2004). Therefore, if adaptability due to bilingual experience is general and not linked to specific language functions (e.g., listening comprehension vs. production), we should see similar performance across both the visual and auditory modalities.

Chapter 2: Method

2.1 Power and Sample Size

To determine how many participants were required to achieve a minimum of 80% power and detect differences in performance across participants, the power analysis conducted (GPower3.1) suggested that approximately 114 participants were required. However, counterbalancing measures required a multiple of 8; therefore, 120 participants were recruited for this study.

2.2 Participants

One hundred twenty-two college-aged participants (M_{age} = 20.6, *SD* = 3.19) attending the University of Texas at El Paso completed this study. However, two participants were excluded from the analyses because of problems conducting their language assessment (one did not complete the assessment, and the other was very familiar with the test). Thus, subsequent analyses include data from the remaining 120 participants. Participants were required to speak at least English and Spanish. Demographics for the sample in the study are reported in Table 1. Participants were recruited through the SONA Research Participation System and were compensated with course credit for their participation. This study was reviewed and approved by the university's institutional review board.

2.3 Study Design

This study followed a 2 (Stroop- and Simon-type task) x 2 (audio and visual modality) within-subjects factorial design. The coefficient of variation (ratio of the standard deviation to the mean) was used to measure participants' reaction time variability, an index of performance stability. Additionally, interference scores (Simon- and Stroop-effects) were computed by subtracting the reaction time of correct congruent trials from correct incongruent trials to reveal the degree of interference caused by irrelevant information. Finally, an analysis of RT for correct incongruent trials was performed to gauge participants' ability to inhibit interference from incongruent information.

2.4 Materials

2.4.1 Language Assessment & Questionnaires

To gauge the bilingual abilities of the participants, their language proficiency was acquired through various measures. First, participants were administered two components of the Woodcock-Muñoz Language Survey-Revised (WMLS-R; Woodcock, Muñoz-Sandoval, Ruef, & Alvarado, 2005): the picture-naming and verbal analogies tests to evaluate their oral language, broad language ability, and language expression skills in English and Spanish. From these subtests, the WMLS-R scoring program was used to calculate an oral language composite score for each language, with reports including age equivalence, cognitive-academic language proficiency, relative proficiency index, percentile rank, and standard score. One of the reported scores, the *W* score (Growth Scale), was used to calculate an individual's degree of balance. This parameter is a special transformation of the Rasch scale (Rasch, 1960), a psychometric model for analyzing categorical data as a function of the trade-off between a participant's abilities and item difficulty (Wright & Stone, 1979). The *W* transformation is closer to a normal distribution and does not suffer the limitation of ceiling effects observed in other scores, such as age equivalence (Schrank, McGrew, & Dailey, 2010). In addition, the equal-interval measurement of the scale and interpretation advantages of Rasch-based measurement (Woodcock, 1982) made this score more robust regarding its psychometric qualities for statistical analysis. We subtracted the W score for Spanish from English in this study and took the absolute value to obtain a measure of relative balance in proficiency across languages. Scores closer to zero were interpreted as reflecting more balanced proficiency levels across both languages, while greater values reflected less balance across languages. Because the aim of the study focused mainly on an individual's degree of balance across languages, other aspects of language experience, such as self-reported dominance, were not incorporated into the analysis and were mainly used for descriptive purposes. While the measure of balance is not aligned with the patterns of language use from the ACH, this measure was chosen under the logic that individuals who are more balanced across languages are likely to encounter more language contexts where they experience cross-language interference, and such experience with language conflict may require them to efficiently engage language control mechanisms to operate in their target language.

In addition to the objective measurement, participants also completed a language assessment questionnaire (see Appendix A) to characterize their use of language in different contexts and tendencies to code-switch. Five of the six sections in this questionnaire were adapted from other questionnaires, including the "Code-Switching and Interactional Contexts Questionnaire" (Hartanto & Yang, 2016), the "Bilingual Switching Questionnaire" (Rodriguez-Fornell, 2012) and a measure of language cooperativeness (Beatty-Martinez, 2021). Lastly, a demographic questionnaire was administered to collect information on gender, age, ethnicity, education, and socioeconomic status.

2.4.2 Apparatus

The tasks were presented on computers running the Windows 11 operating system. The experiment was programmed using E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA). The tones for both audio tasks were generated as a sine waveform with the chirp option using Audacity® 3.1.2 software (Audacity Team, 2021). The stimuli for the visual tasks were created as an animated shape in a slide using Microsoft PowerPoint and uploaded to E-Prime software as a movie file.

2.5 Stimulus-Stimulus (Stroop) tasks

Participants completed visual and auditory non-linguistic Stroop-type tasks that involved stimulus-stimulus (S-S) interference. In the visual version of this task, participants viewed a square on the computer screen that could move higher or lower from its original position. Participants had to respond to the direction the square moved. Participants sat approximately 20 inches away from the monitor. On each trial, a fixation point appeared in the center of the monitor for 750 milliseconds. Then a ½" x ½" square was displayed above or below the fixation point that subtended 3.8 degrees of visual angle in the vertical and horizontal dimensions. The square would either move to a higher or lower position relative to its starting point as it was displayed. This presentation lasted 250 milliseconds before the square disappeared from the screen. Movement direction was manipulated in this task to be congruent or incongruent with the initial position of the square relative to the fixation point to create two congruent trials (a high starting square where the square moved higher or a low starting square where the square moved lower) and two incongruent trials (a high starting square where the square moved lower or a low starting square where the square moved higher) (see Figure 1). The subsequent trial did not begin until the participant submitted a response.

In the auditory version of this task, participants wore over-the-ear headphones and listened to high- or low-pitched tones. The pitch shifted higher or lower relative to the initial pitch, and participants had to respond to the direction in which the pitch shifted. At the start of each trial, a fixation point appeared in the center of the monitor for 750 milliseconds. Participants then heard a tone with a frequency of either 1800 Hz (high pitch) or 600 Hz (low pitch). The pitch then shifted higher or lower by 200 Hz from the starting pitch (e.g., 1800 Hz would shift to 2000 Hz for a high-pitch tone shifting higher). The presentation of the tones lasted 250 milliseconds. Participants had to make their response before the next trial was initiated. The direction of pitch change was manipulated in this task to be congruent or incongruent with the initial relative pitch of the starting tone to create two congruent trials (a high-pitched tone shifting higher or a low-pitched tone shifting lower) and two incongruent trials (a high-pitched tone shifting lower or a low-pitched tone shifting higher) (see Figure 1).

2.6 STIMULUS-RESPONSE (SIMON) TASKS

Similarly to the Stroop-type paradigm, participants also completed a visual and auditory Simon-type task where conflict exists between the spatial positioning of the stimulus location and the spatial position of the required response key on the keyboard, creating stimulus-response (S-R) interference. In the visual version, participants sat approximately 20 inches away from the monitor. A ½" x ½" square was shown on the screen and subtended 3.8 degrees of visual angle in the vertical and horizontal dimensions. A fixation point appeared in the center of the monitor for 750 milliseconds, followed by the square above or below the fixation point for 250 milliseconds before disappearing from the screen. The square appeared towards the left or right side of the monitor, thus allowing for location manipulation to be congruent or incongruent with the spatial positioning of the required response key on the keyboard to create two congruent trials and two incongruent trials (see Figure 2).

In the auditory modality version, participants wore over-the-ear headphones and listened to high or low-pitched tones with frequencies of 1400Hz and 700Hz, respectively. A fixation point appeared in the center of the monitor for 750 milliseconds, and each tone had a duration of 250 milliseconds. Similar to the visual modality, the position of the tone presented (i.e., the left or right ear) was manipulated to be congruent or incongruent with the spatial positioning of the required response key (see Figure 2).

2.7 Procedure

Each participant was tested individually in a quiet room with a bilingual research assistant. Participants first completed the informed consent, followed by the demographics questionnaire. Participants then completed the picture-naming and verbal analogies sub-tests of the Woodcock-Muñoz language assessment. Once the language proficiency scores in English and Spanish were collected, participants were then instructed that they were going to complete a series of tasks on a computer. Participants put on the headphones and were shown the proper hand placement on the keyboard in order to make their responses.

Participants were informed that they would either see or hear different stimuli for the computerized tasks and then respond based on what they experienced. For the Stroop-type tasks, because responses were based on the direction of pitch change or square movement, participants were instructed to press the ‘Q’ key on a keyboard for a higher-shifting stimulus (e.g., a high starting square/pitch going higher) and the ‘P’ key for a lower-shifting stimulus(e.g., a low starting square/pitch going lower). On the other hand, for the Simon-type tasks, participants were instructed to press the ‘Q’ key if the square was above the fixation point or the tone was high pitched, and the ‘P’ key if the square was below the fixation point or the tone was low pitched. The stimuli were presented unilaterally (i.e., observed on one side of the monitor or heard from one ear only); therefore, a congruent trial involved, for example, a square above the fixation point towards the left side of the monitor (which required a left key ‘Q’ response). In contrast, an incongruent trial comprised a square above the fixation point towards the right side of the monitor (still requiring a left key ‘Q’ response).

Participants completed 16 practice trials (half congruent and half incongruent) and 200 experimental trials (100 congruent and 100 incongruent) in each of the four tasks (Simon visual, Simon auditory, Stroop visual, and Stroop auditory). The four types of trials within each task were presented randomly. Since the response keys needed to be spatially consistent (or not) with the location of the stimulus for the Simon task, the response keys corresponding to the "higher" or "lower" judgments were the same across the Stroop and Simon tasks to allow for comparisons within participants. To diminish any effects of fatigue, participants were allowed to take a break after each set of 50 trials. The order of the four tasks was counterbalanced across participants. After the computer tasks, participants were given the language assessment questionnaire and, lastly, an exit questionnaire that asked for general comments before being debriefed on the intentions of the study.

Chapter 3: Results

3.1 Data Coding & Analysis

The coefficient of variation (CoV) served as the measure of performance stability and was calculated within each participant by calculating the standard deviation across all reaction times (for both correct and incorrect trials and across all trial types) and dividing by their mean reaction time. Higher scores in this measure indicate more variability observed in participants' responses or poorer performance stability. Interference scores is a collective term that references Stroop and Simon effects that measure the extent to which irrelevant information interferes with the processing of congruent information. Only correct trials for both congruent and incongruent conditions were used in this metric. Lastly, only correct trials were used for the analysis in RT of incongruent trials.

The analysis for the above-mentioned variables involved using a 2 (task) x 2 (modality) repeated measures ANOVA to explore the impact of task and modality on performance before considering the impact that different language factors can have on these outcome measures. Then, the different language components (i.e., degree of balance, context of use [see Section 3.2 Factor Analysis]), were incorporated in ANCOVAs to measure how language experience moderates these effects. Finally, post-hoc pairwise comparisons using Bonferroni adjustments for significance were performed in cases where significant main effects or interactions were observed.

A Kolmogorov-Smirnov test revealed that the distribution of the degree of balance departed significantly from normality ($W([120] = 0.129, p < .001)$). Based on this outcome, a square-root transformation was applied to the balance scores, making them more uniform. Additionally, scores for all language components were centered around the mean to decrease the inflation of Type I error rates and mitigate the loss of power that can arise when evaluating the effects of within-subjects design when performing an analysis of covariance (Schneider et al., 2015). Lastly, screening for outliers was performed by removing trials where RTs were less than 200ms or exceeded three standard deviations from the mean of the distribution. This cutoff point removed, on average, 2% of trials per participant per task. The number of removed trials is well under the acceptable limit in eliminating outliers (Ratcliff, 1993) and can increase the statistical power of the results (Van Zandt, 2002).

3.2 Factor Analysis

An exploratory factor analysis was performed on the subjective language assessment to identify factors that would reflect specific language patterns of participants. Bartlett's test of sphericity was found to be significant (χ^2 [276] = 1237.491, $p < .001$), indicating the use of a factor analytical model is suitable, and Kaiser-Meyer-Olkin measure of sampling adequacy shows a moderate relation amongst variables (*KMO* = 0.75), which deemed the number of participants relative to the number of items as appropriate, demonstrating the questionnaire befits this analytical approach. The latent variables discovered in this stage were incorporated into the subsequent analyses as covariates to determine how language use in these contexts modulated performance on the nonlinguistic attentional control tasks. The criteria to decide on the correct number of factors for retention was based on recommendations provided by Costello & Osborne (2005).

The EFA was performed using direct oblimin rotation and maximum likelihood extraction; examination of a scree plot suggested a two-factor solution as the best-fitting model (CFI= 0.637; SRMR= 0.081; RMSEA= 0.118). Following a suggestion by Tabachnick & Fidell (2001), only items loaded onto a factor with a value of 0.32 or higher were included. As a result, three items were deleted from the analysis (Items 11, 14, and 25; see Appendix A). As seen in Appendix B, the first factor appears to capture the use of language in situations where people may not need to exercise much control over the non-target language. In contrast, the second factor reflects situations where more language control may be required to communicate effectively. Given this pattern, the first factor was identified as ‘low language control context,’ comprised of 11 items with an eigenvalue of 5.947, accounting for 24.78% of variance in the data. The second factor was labeled ‘high language control context,’ consisting of 10 items with an eigenvalue of 1.68, accounting for an additional 6.99% of the variance.

3.3 Coefficient of Variation (CoV)

The results yielded a main effect of task type, $F(1, 119) = 26.91$, $p < .001$, $\eta^2_p = .18$; participants showed higher CoV (i.e., lower performance stability) in the Stroop ($M = .40$, $SE = .01$) than the Simon ($M = .34$, $SE = .01$) task. There was also a main effect of modality, $F(1, 119) = 30.09$, $p < .001$, $\eta^2_p = .20$, where higher variability was observed in the auditory ($M = .40$, $SE = .01$) than the visual ($M = .33$, $SE = .01$) versions of the tasks. There was also a significant interaction between task and modality, $F(1, 119) = 26.07$, $p < .001$, $\eta^2_p = .18$, whereby modality of the task influenced CoV only in the Stroop task. The post hoc analysis indicated that the auditory modality showed a significant decrease in stability performance from the Simon- to Stroop-type auditory task, $t(119) = 6.7$, $p < .001$, but not in the visual one, $t(119) = 0.95$, $p = .346$, implying that participants showed more variation in the auditory Stroop task than the visual task while performance was equivalent across modalities within the Simon task (see Figure 3).

An ANCOVA including degree of balance as a between-subjects covariate failed to modulate any of these effects (all $p > .1$). However, degree of balance did have an effect on overall CoV, $F(1, 118) = 4.72$, $p < .032$, $\eta^2_p = .04$. Namely higher degree of balance scores (indicating lower relative balance in proficiency across languages) was associated with lower CoV (see Figure 4), signifying that less-balanced bilinguals are more stable in their performance than their more balanced counterparts, $R^2 = 0.135$, $p = 0.003$. ANCOVAs, which included the low language control factor and the high language control factor from the language assessment questionnaire as between-subjects covariates, revealed no significant modulation of the task and modality effects on CoV and no relationship with CoV performances (all $p > .1$).

3.4 Interference Scores

The repeated-measures ANOVA revealed a main effect of task, $F(1, 119) = 50.56$, $p < .001$, $\eta^2_p = .30$, due to larger interference scores in the Stroop ($M = 114.13$, $SE = 7.63$) than Simon ($M = 60.76$, $SE = 3.15$) task. There was also a reliable effect of modality, $F(1, 119) = 73.15$, $p < .001$, $\eta^2_p = .38$, with larger interference scores for the auditory ($M = 123.6$, $SE = 8.01$) than the visual ($M = 51.29$, $SE = 3.39$) tasks. Further, a two-way interaction emerged between task and modality, $F(1, 119) = 52.97$, $p < .001$, $\eta^2_p = .31$. Post hoc analysis reveals a larger interference score in the auditory modality over the visual for the Stroop task, $t(119) = 8.45$, $p < .001$, as well as the Simon task, $t(119) = 2.71$, $p < .001$ (see Figure 5).

The addition of degree of balance as a covariate modulated the main effect of task, $F(1, 118) = 5.40$, $p = .027$, $\eta^2_p = .04$, and the interaction between task and modality, $F(1, 118) = 4.43$, $p = .037$, $\eta^2_p = .04$. As shown in Figure 6, degree of balance was associated with interference scores primarily in the auditory Stroop task, with less balanced individuals showing smaller interference scores. While the low and high language control factors did not moderate any of the task or modality effects or their interactions (all $p > .1$), high language control factor scores were significantly associated with interference score, $F(1, 118) = 6.64$, $p = .011$, $\eta^2_p = .05$. Figure 7 shows a positive relation between this covariate and interference score, where individuals with higher scores on the high-language control factor (those who experience more contexts in which they have to exercise high language control) experienced higher levels of interference in the experimental tasks.

3.5 Reaction Time For Incongruent Trials

The repeated-measures ANOVA yielded a main effect of task, $F(1, 119) = 145.18$, $p < .001$, $\eta^2_p = .55$, due to participants making slower responses on incongruent trials in the Stroop task ($M = 741.48$, $SE = 18.24$) than in the Simon task ($M = 581.43$, $SE = 12.75$), as well as a main effect of modality, $F(1, 119) = 109.63$, $p < .001$, $\eta^2_p = .48$, with participants taking longer on incongruent trials in the auditory ($M = 734.66$, $SE = 18.88$) than the visual ($M = 588.26$, $SE = 12.19$) modality. In addition, a two-way interaction emerged between task and modality, $F(1, 119) = 68.82$, $p < .001$, $\eta^2_p = .37$. The post hoc analysis indicates that the degree to which RT differed as a result of modality was larger in the Stroop task, $t(119) = 10.45$, $p < .001$, than the Simon task, $t(119) = 3.91$, $p < .001$; participants had longer RTs for incongruent auditory Stroop trials than incongruent visual Stroop trials, and while present, this difference was smaller across modalities within the Simon task (see Figure 8).

For the analysis incorporating the language components, degree of balance modulated the main effect of modality, $F(1, 118) = 4.06$, $p = .046$, $\eta^2_p = .03$, and the interaction between task and modality, $F(1, 118) = 5.03$, $p = .027$, $\eta^2_p = .04$. As shown in Figure 9, degree of balance was found to modulate RTs for incongruent trials mainly in the auditory Stroop task; participants that are more balanced across their two languages took longer to make a correct response in this condition than individuals who were more balanced in proficiency across English and Spanish. Low and high language control factors did not moderate any of the task or modality effects or their interactions and were not found to be associated with this dependent variable (all $p > .1$)

Chapter 4: Discussion

This study aimed to determine how aspects of the bilingual experience, particularly degree of balance across two languages and experience in different language use contexts, may impact performance in visual and auditory nonlinguistic attentional control tasks. This study operationalized bilingualism in these ways to capture more attributes related to the complexity behind one's language experience. Both auditory and visual task versions were used to explore whether performance differences generalize across modalities or appear isolated to one. Whereas prior research has looked at group differences based mainly on reaction time and accuracy outcomes, this study incorporated standard reaction time-based measures and a measure of performance stability to assess attentional control (Hultsch, MacDonald, & Dixon, 2002). As prior studies have reported that specific inhibitory mechanisms are affected more than others as a result of bilingualism (Blumenfeld & Marian, 2014), we hypothesized that balanced bilinguals would show more stable performance on a nonlinguistic task that requires resolving two conflicting dimensions of the same stimulus than a task where conflict occurs between different stimulus dimensions. Our results are inconsistent with this prediction. Instead, we observed that participants who are more balanced across their two languages are more variable (less stable) in their responses than less balanced bilinguals. In particular, our findings suggest that the modulation of language measures primarily occurs in the auditory Stroop-type task, as evidenced by the observed task and modality effects and their interactions. In addition, we observed that participants with more experience operating in a high language control environment show higher interference scores. Given that the results are not entirely in accord with the existing literature, we offer the following explanations to account for these discrepancies.

4.1 (Language) Context Matters

Our results can be rationalized using the adaptive control hypothesis (ACH) (Green & Abutalebi, 2013), which further exemplifies the importance of context for language control. In their explanation of behavioral and neurocognitive adaptations, it is postulated that SLC users recruit domain-general mechanisms (i.e., goal maintenance, conflict monitoring, and interference suppression), DLC speakers additionally engage in selective response inhibition and task disengagement, and that DCS users do not heavily rely on inhibitory control which allows both languages to remain active and either be produced (Paap, Mason, & Anders-Jefferson, 2021).

To explain the results observed in our study, we focus on the last two communication patterns in the ACH, which closely resemble the patterns in which participants reported engaging. Although these patterns relate to using two languages in the same environment, the level of activation for each language varies significantly. Our participants' experiences demonstrate that bilingual speakers are unlikely to only adapt to one specific pattern from the ACH, and exclusively classifying bilingual speakers to just one contexts may not be appropriate. Adapting to multiple styles may have unique effects that allow bilingual speakers to meet the environmental demands of language control. As a result, the constant switching between communication profiles may lead to adaptations not previously speculated in the original proposition. However, the outcomes of speakers adapting to multiple patterns are still unclear, and the conclusion that the mixture of both patterns may reflect (and possibly obscure) the outcomes observed in this study remains speculative.

This same proposition of adaptive changes may also account for the relation between high language control and interference scores results observed in our study. Recall that the high language factor encompasses communication patterns where more control is exerted to communicate effectively, particularly in professional environments like work or school. While the ACH posits that adaptive changes occur to meet environmental demands, the observed effect may not be exclusive to the study setting but rather influenced by the study design. Specifically, since participants completed the language assessment in both languages, they may have inadvertently been placed in a high language control state, which left fewer resources available for attentional control during the tasks and resulted in a greater impact of interference across all modalities. To mitigate this issue, a more optimal approach could involve administering the language assessments in only one language before the attentional control tasks and the other language after or administering both assessments after the computer tasks to avoid participants using attentional resources that may limit their ability to perform the computer tasks successfully. In addition, strategies that participants reported in the exit questionnaire, such as having difficulty recalling words in one language when exposed to the other and relying on remembering how to use a word in a sentence, suggest that some interference was already experienced before the attentional tasks, supporting the notion that the study design may have an impact on the results.

4.2 The Importance of Choosing Effective Tools

Our study underscores the importance of diversity and variability in language by examining the impact of degree of balance in proficiency across languages on nonlinguistic attentional control tasks. Rather than comparing monolinguals and bilinguals, our study focused on bilinguals with varying degrees of balance and different contextual experiences. Given how degree of balance moderates the effects we see in our outcome measures that are inconsistent with prior work, this study exemplifies the importance of using more meaningful assessments of bilingual experience that encompass more aspects of language that can achieve different results.

Other researchers support the use of degree of balance as a meaningful way to evaluate bilingual experience (Birdsong, Gertken, & Amengual, 2012) with the claim that variability of language is a partial representation of the variability in individuals, highlighting the importance of taking into account the complexity of the bilingual experience for future research (Bialystok, 2011).

Along with the proper way to operationalize language, our study highlights the importance of proper task selection in examining performance differences between monolinguals and bilinguals. For example, whereas Blumenfeld & Marian (2014) reported that bilinguals show smaller Stroop than Simon effects compared to monolinguals, our results do not support these findings. However, it is important to note that the task they used (Spatial Arrow Task) contains conflict in both stimulus and response dimensions, which is why it is referred to as both Spatial Stroop and Spatial Simon tasks in the literature (Hilchey & Klein, 2011). Although minor modifications in the methodological approach were made, our study should still show similar results to those in the literature, yet given that they do not, this brings forth the issue that even different ways of looking at performance may affect the outcomes in behavioral studies. Recent conceptualizations of the consequences of bilingual language experience suggest that bilinguals may develop greater attentional control and flexibility due to the need to constantly manage and switch between two languages (Bialystok & Craik, 2022). Instead of just one particular cognitive domain, this new framework is robust in that it conceptualizes attentional control as a multifaceted construct consisting of various functional processes, including working memory, facilitation, inhibition, and selection (Bialystok & Craik, 2022). The visual and auditory Stroop and Simon tasks align with this conceptualization because they tap into attentional control processes to manage conflicting information and inhibit irrelevant responses. Therefore, these tasks can be appropriate in examining how bilingualism affects attentional control and can help us better understand the cognitive consequences of bilingual language experience. By analyzing cases in which bilingual adaptations have been observed and instances where they have not, this framework seeks to explain these results and help elucidate the inconsistent findings in the literature.

One of the strengths of our study is that we compared within-subjects performance across two attentional control tasks and two modalities to address some of the issues found in variability. Our results showed that participants had more difficulties with the Stroop auditory condition, suggesting that this task is more challenging for college-aged participants. This can be seen in our results, where participants consistently performed poorer on the Stroop auditory task on all dependent measures compared to other tasks and modalities. Since some researchers argue that the reason young adults fail to show adaptations in EF tasks is because they are at their peak of cognitive efficiency (Bialystok et al., 2005), our results show that the Stroop audio task has the potential to become a valuable tool in future studies when looking at individual differences in this population.

To our knowledge, this study is the first to consider how various components of bilingual language experience (i.e., degree of balance and contextual use) may influence performance on traditional tasks to assess the ability to resolve conflict in two modalities. First, our findings indicate that individuals with a more balanced proficiency in both languages experienced more disruption by conflict across all task conditions and moderated task and modality effects for interference scores and incongruent reaction time trials. In particular, this effect seemed primarily driven by modulation of performance within the auditory Stroop task. Our findings suggest that young bilinguals may find this task more challenging. One plausible explanation for this is that the participants self-reported being in a high language control environment during the study, which could have required the allocation of additional cognitive resources. This may have resulted in reduced availability for other activities and potentially contributed to the observed difficulty in completing the task. In other words, because they are already exerting more effort to control their use of language in a high language control environment, they may have fewer resources available to effectively filter out interfering information in a nonverbal attention control task. This explanation is supported by our results, which demonstrate that participants who reported higher language control environments displayed larger interference scores. Alternatively, it may be that the control mechanisms thought to benefit from jointly activated languages are more language-specific than initially hypothesized. It is possible that individuals who have more experience in high language control environments may have adapted to a processing style that prioritizes language processing at the expense of other cognitive processes. This may make it more difficult for them to switch their attention away from language processing and toward the nonverbal attention control task, which could also contribute to increased interference scores. Lastly, Green and Abutalebi (2013) state that speakers of single- and dual-language contexts should display increased skill in the control of interference, but given that our participants identified an environment where code-switching behaviors occur every day, this prolonged exposure in this pattern may limit the adaptive changes in control that are captured in their performance.

4.3 Limitations

While these results provide more insight into the knowledge of bilingualism and cognitive adaptations, it is advisable to approach their interpretation with caution. Firstly, we only used two subtests from the WMLS-R to measure the bilingual experience objectively. Even though the assessments measured different aspects of language (i.e., picture vocabulary determined language development and lexical knowledge; verbal analogies assessed reasoning and language comprehension) (Woodcock, Muñoz-Sandoval, Ruef, & Alvarado, 2005), the inclusion of additional tests could lead to a more comprehensive and representative score of an individual's language abilities. Secondly, participants were recruited from an environment where both languages are widely accessible and frequently utilized, which could restrict the applicability of our results to bilingual individuals who reside in highly multilingual environments. Therefore, this study can benefit from being replicated in an environment with more SLC or DLC speakers to observe the outcomes of these different context patterns.

4.4 Future Directions

In light of the results of this study, it may be worth exploring if the moderation effects between language components and performance on attentional control tasks are replicated with other measures of balance. While researchers argue for treating language as a continuous variable (Baum & Titone, 2014), there are divergences in practice regarding what components are used to capture a bigger picture of someone’s language abilities. For example, Birdsong and colleagues (2012) developed the Bilingual Language Profile, a comprehensive subjective assessment that measures language history, use, proficiency, and attitudes that yield a global index of language dominance that can capture more aspects of the bilingual experience.

Similarly, there may be value in using different tasks to reflect different attentional control processes that are also commonly used in this line of research. Some researchers argue that the weight of the evidence in the literature makes inhibitory control an inadequate mechanism to explain bilingual adaptations and instead shifts the focus toward attentional control (Bialystok & Craik, 2022). Therefore, tasks such as the AX-CPT are better suited to explore goal maintenance and conflict resolution, where better bilingual performance is reported in the literature (Bialystok, 2017). Some studies investigating different inhibition mechanisms (i.e., active and reactive inhibition) in bilinguals and monolinguals support the usefulness of such a task when no differences between language groups are reported in terms of active inhibition but demonstrate a better ability to maintain goals (Colzato et al., 2008).

4.5 Conclusions

In this study, we aimed to investigate the impact of language balance on attentional control tasks across different modalities. Instead of categorizing bilinguals as either having or lacking a second language, we took a continuous approach to capture the complexity of the language experience. Our findings suggest that measuring variability can provide a more comprehensive understanding of performance differences, and dichotomizing bilingualism may not be the most appropriate method. The study sheds light on the diverse nature of bilingualism and emphasizes the need to consider multidimensionality in research design and tools to account for the inconsistencies in the literature.

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Table 1
Participant Characteristics

Characteristic	Frequency
Age (*SD*)	20.667 (3.19)
Gender (%)	
Male	34 (28.33)
Female	86 (71.67)
Ethnicity (%)	
American Indian/Alaskan Native	3 (2.5)
Asian	0 (0)
Native Hawaiian/Pacific Islander	0 (0)
Black/African American	0 (0)
White/Caucasian	8 (6.67)
More than one race	10 (8.33)
Prefer not to respond	25 (20.83)
Language Traits (%)	
English as L1	22 (18.3)
Spanish as L1	97 (80.83)
Other as L1	1 (0.83)

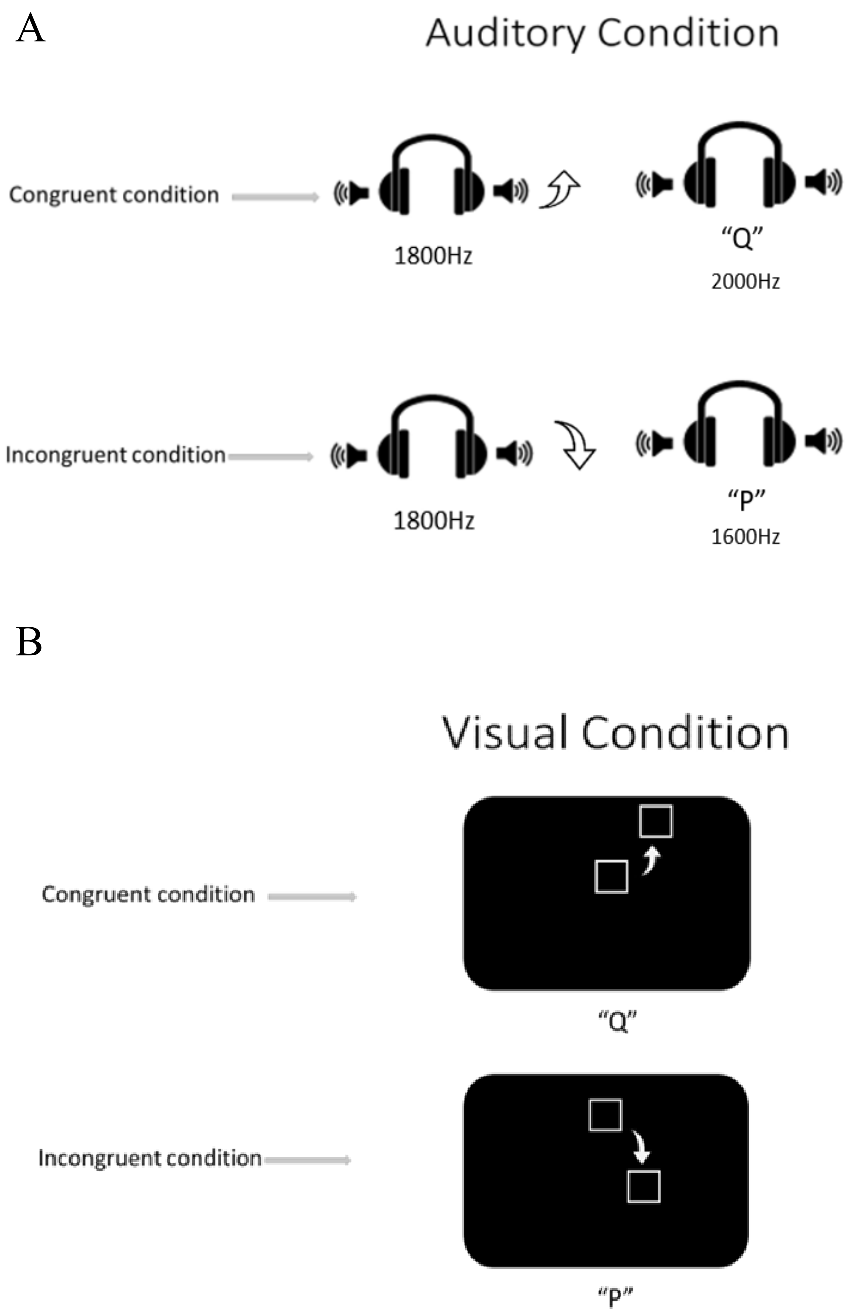

Figure 1: Schematic of the Stimulus-Stimulus (Stroop-type) task. A: Representation of the Stroop-type auditory condition. B: Representation of the Stroop-type visual condition. The square moves exclusively on the vertical dimension. Arrows are for demonstration purposes and do not appear on any of the trials.

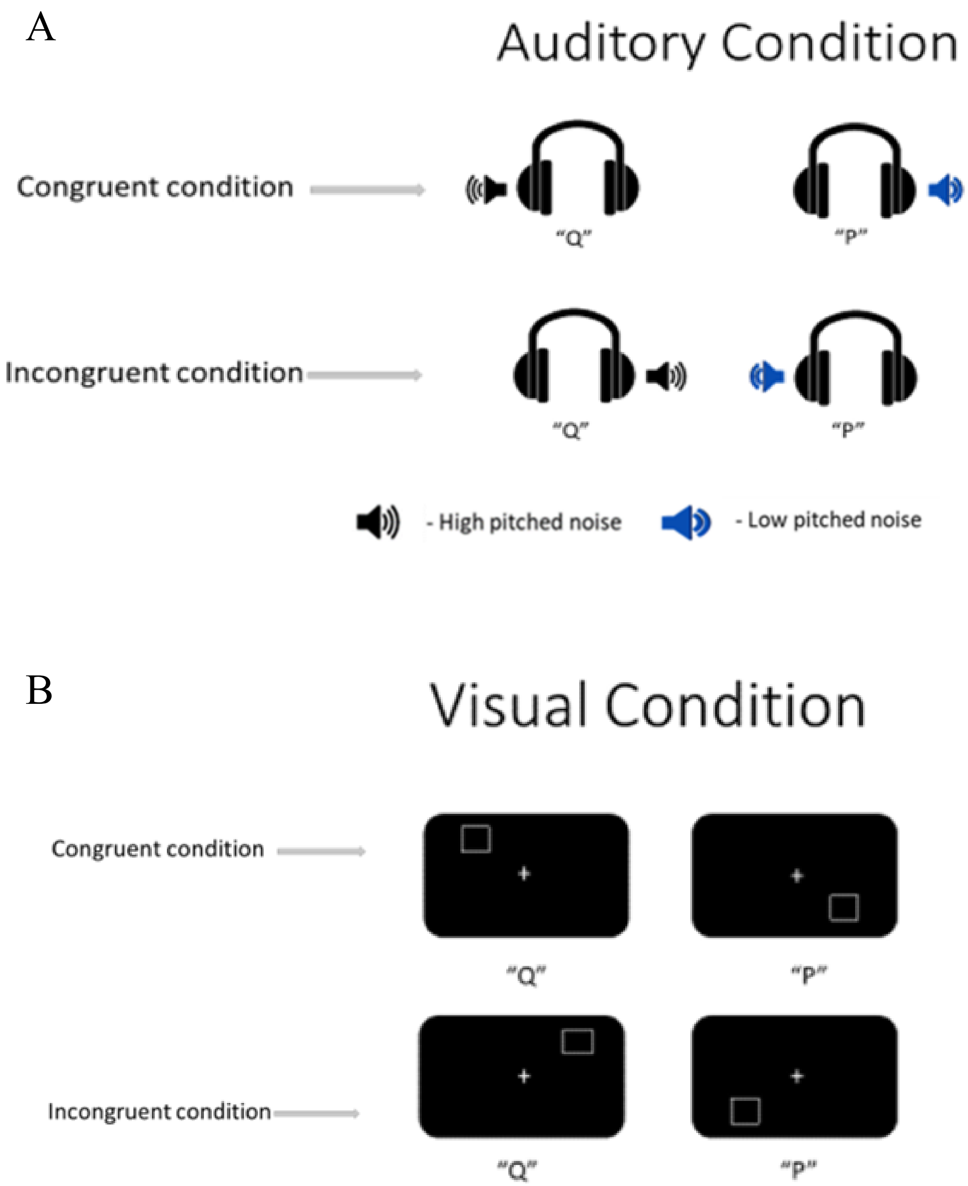

Figure 2: Schematic of the Stimulus-Response (Simon-type) task. A: Representation of the Simon-type auditory task. B: Representation of the Simon-type visual task.

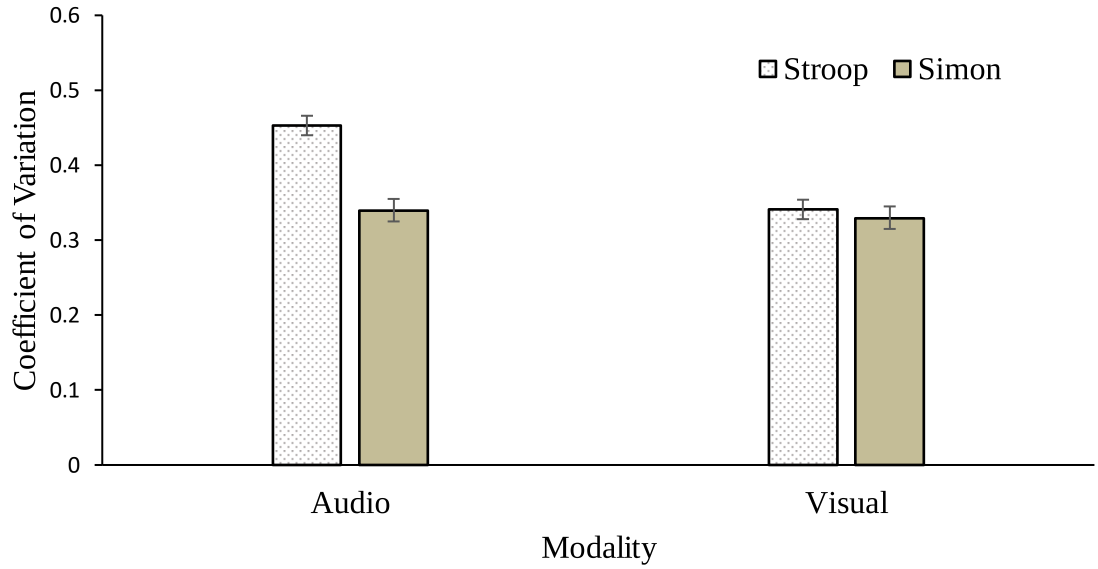

Figure 3: Coefficient of Variation by Task and Modality. Higher values of CoV indicate poorer stability. Error bars represent standard error.

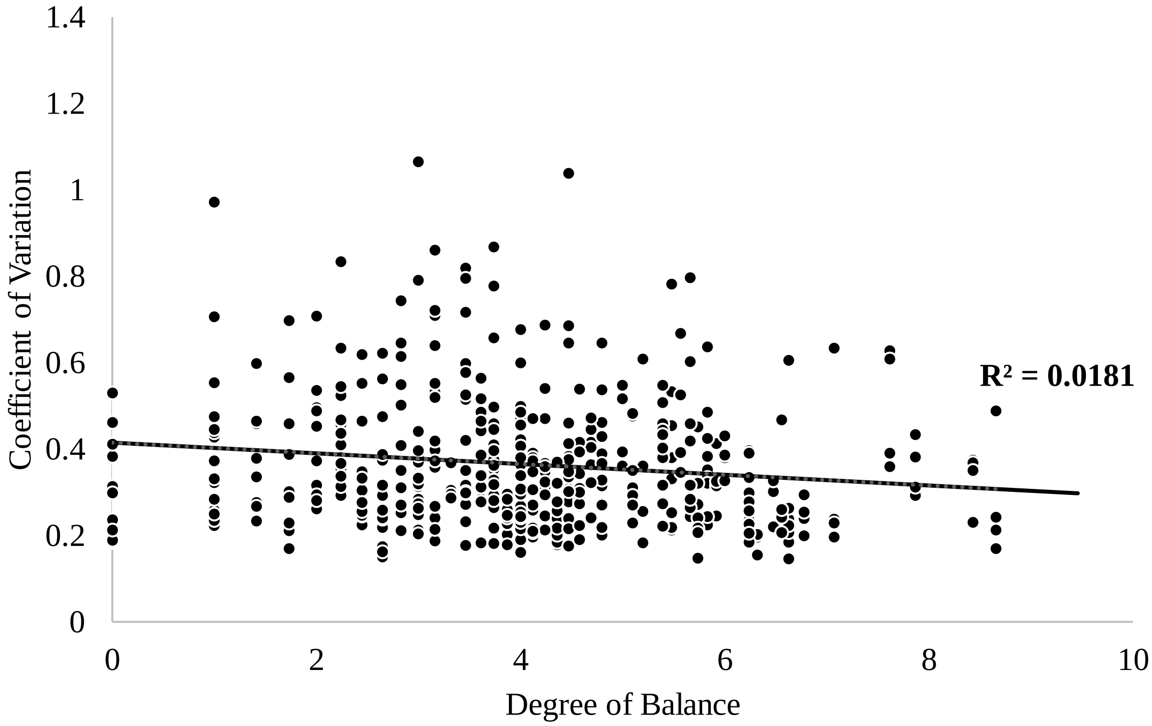

Figure 4: Scatterplot showing the relation between Degree of Balance and CoV. Higher scores of CoV represent poorer stability. Conversely, lower values of degree of balance represent more relative balance in proficiency across the two languages.

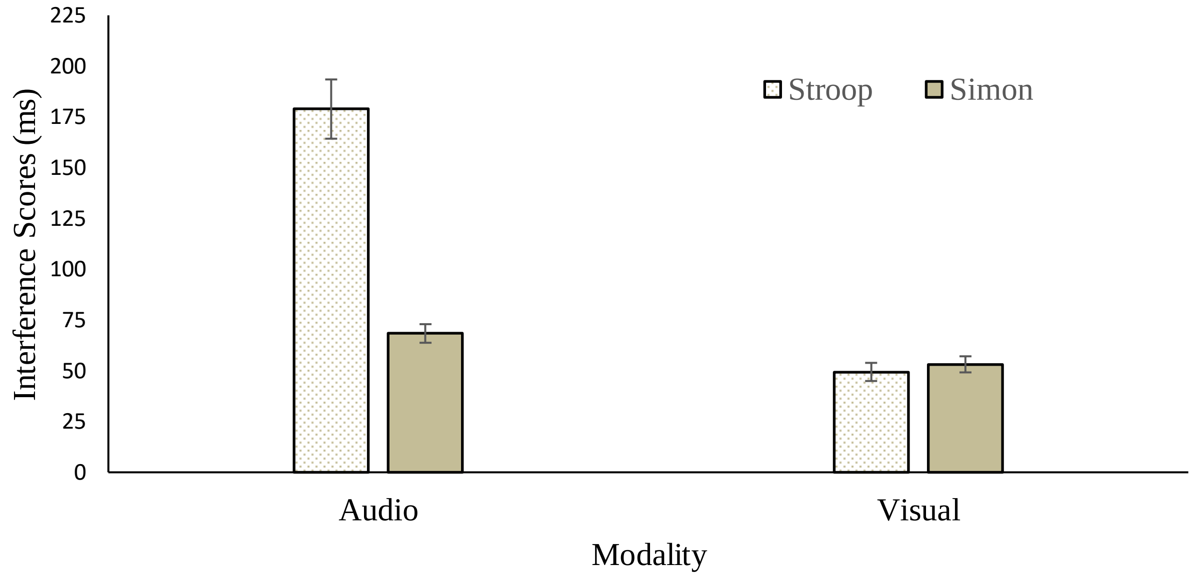

Figure 5: Interference Scores by Task and Modality. Error bars represent standard error.

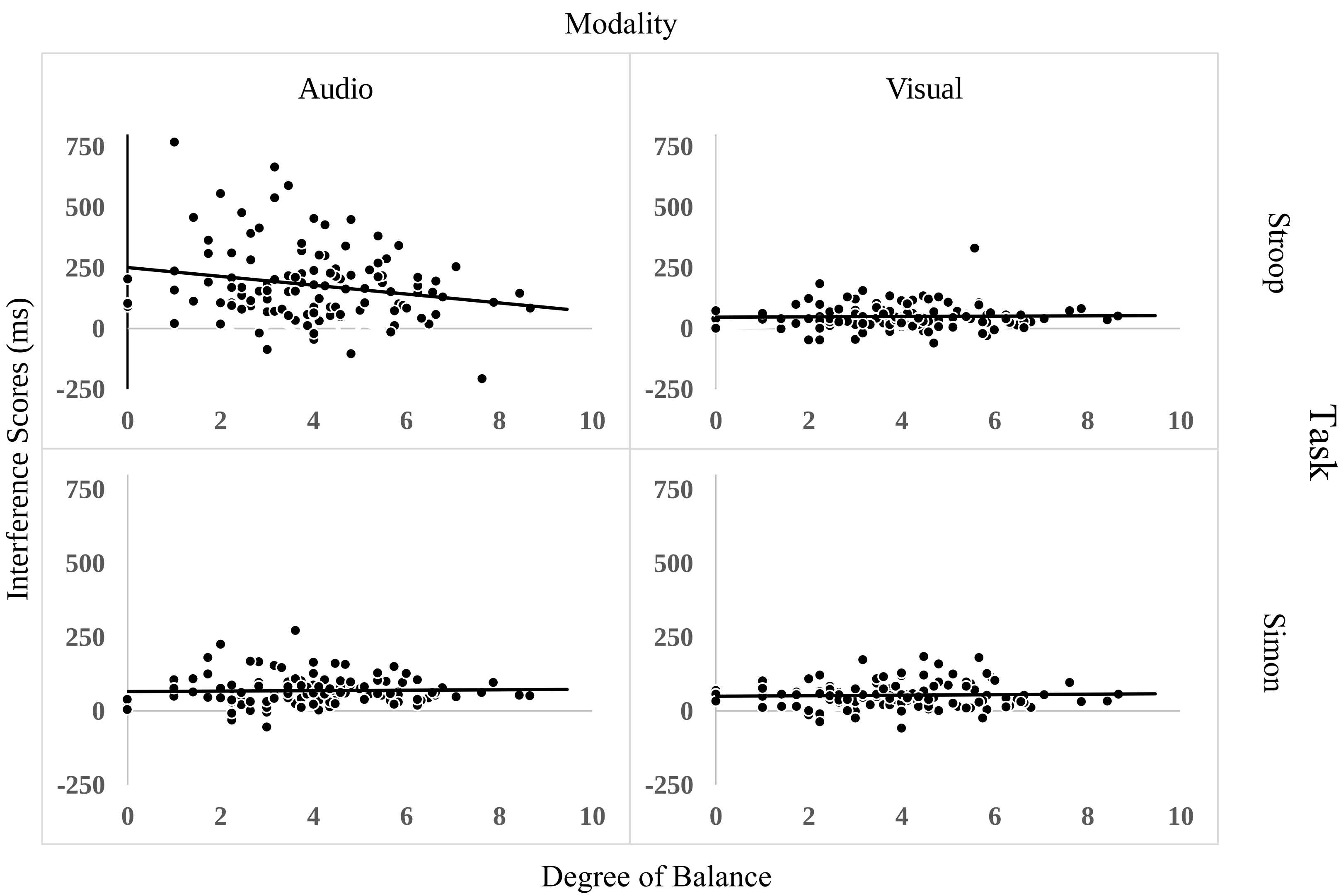

Figure 6: Relation between Degree of Balance and Interference Scores

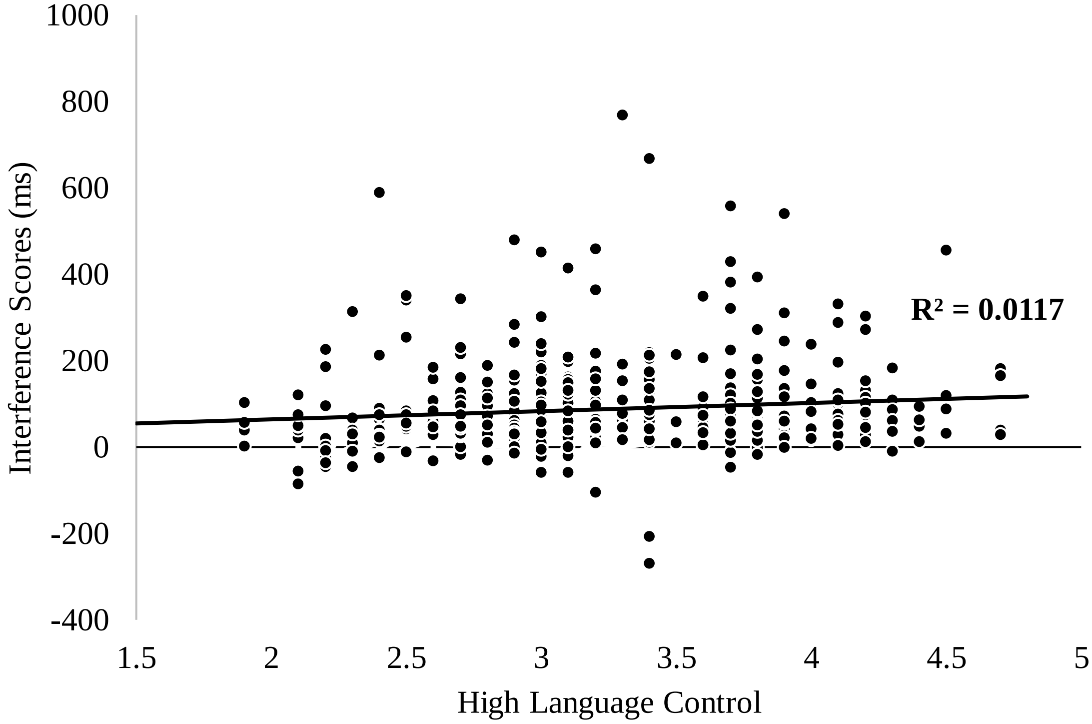

Figure 7: Scatterplot showing the relation between High Language Control and Interference Scores.

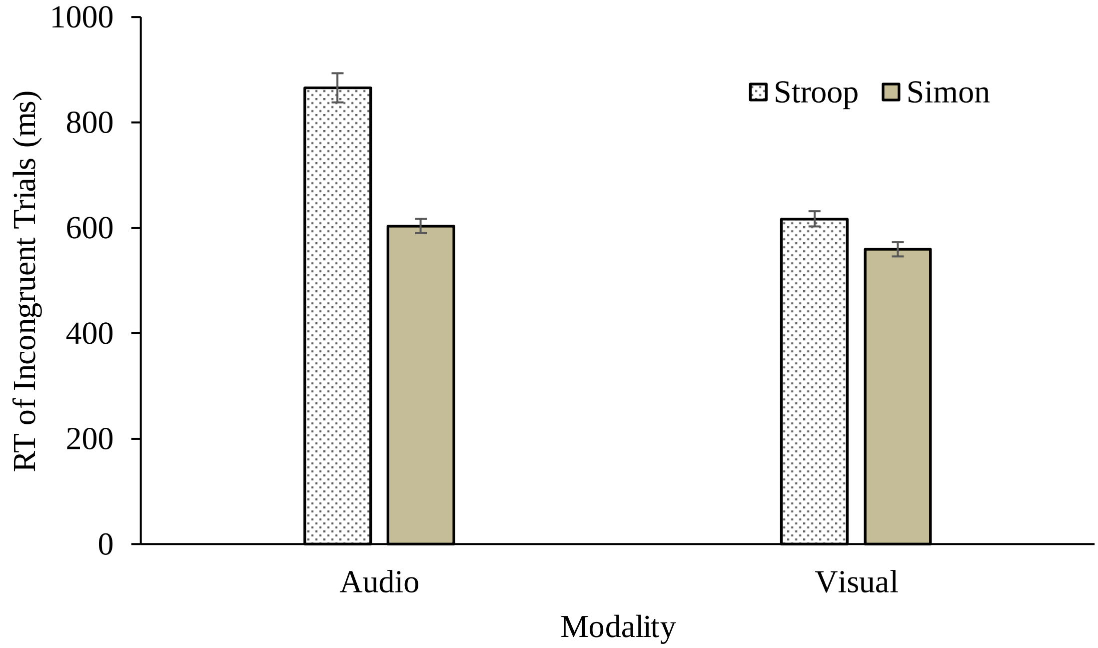

Figure 8: Correct Incongruent Trials by Task and Modality. Error bars represent standard error.

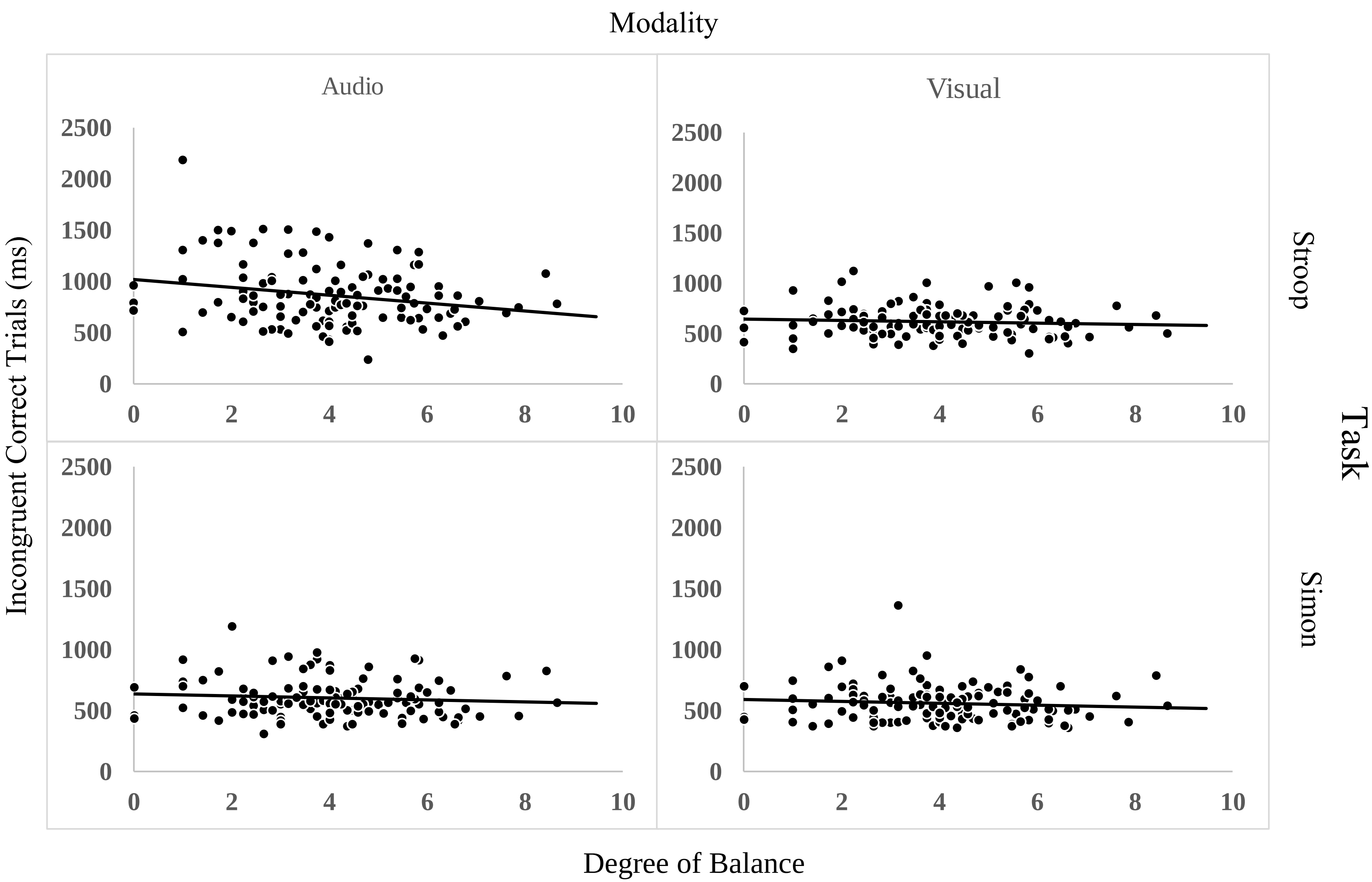

Figure 9: Task and Modality on Incorrect Congruent Trials

Appendix A
Language Assessment Questionnaire

1. Identify which is your:

Native language: ______________________________
Second Language: _____________________________ (Fluent: ____ Yes ____ No)
Third Language: _______________________________ (Fluent: ____ Yes ____ No)
Fourth Language: ______________________________ (Fluent: ____ Yes ____ No)
Strongest language: ___________________________

Intersentential Code-Switching
Using the scale below, mark your answers based on the following question:

- How often do you switch languages between sentences when speaking at ____?

	Never	Rarely	Sometimes	Most of the Time	Always
2. Home (e.g., you speak one sentence in English and another sentence in Spanish)	1	2	3	4	5
3. School (e.g., you speak one sentence in English and another sentence in Spanish)	1	2	3	4	5
4. Work (e.g., you speak one sentence in English and another sentence in Spanish)	1	2	3	4	5
5. In places other than home, school, and work (e.g., you speak one sentence in English and another sentence in Spanish)	1	2	3	4	5

Intrasentential Code-Switching
Using the scale below, mark your answers based on the following question:

- How often do you mix words of different languages when speaking at ___?

	Never	Rarely	Sometimes	Most of the Times	Always
6. Home (e.g., if you have trouble finding a word in Spanish, you replace it with an English word, or vice versa)	1	2	3	4	5
7. School (e.g., if you have trouble finding a word in Spanish, you replace it with an English word, or vice versa)	1	2	3	4	5
8. Work (e.g., if you have trouble finding a word in Spanish, you replace it with an English word, or vice versa)	1	2	3	4	5
9. In places other than home, school, or work (e.g., if you have trouble finding a word in Spanish, you replace it with an English word, or vice versa)	1	2	3	4	5

Composite Score of Dual-Language Context

Using the scale below, mark your answers based on the following question:

- How often do you ______:

	Never	Rarely	Sometimes	Most of the Times	Always
10. Speak two or more languages in the same environment (e.g., using both English and Spanish at school)?	1	2	3	4	5
11. Speak only one language in one environment (e.g., Spanish at home and English at school)?	1	2	3	4	5

Bilingual Switching Assessment

For each of the questions below, circle the response that best characterizes how you feel about the statement

	Never	Rarely	Sometimes	Most of the Times	Always
12. I do not remember some English words when speaking this language	1	2	3	4	5
13. I do not remember some Spanish words when speaking this language	1	2	3	4	5
14. When I cannot remember a word in English, I produce it in Spanish	1	2	3	4	5
15. When I cannot remember a word in Spanish, I produce it in English	1	2	3	4	5
16. I do not realize when I switch languages during conversation	1	2	3	4	5
17. I do not realize when I mix languages during conversation	1	2	3	4	5
18. It is difficult to control the language switches in a conversation	1	2	3	4	5
19. Without realizing, I produce the Spanish word faster when speaking English	1	2	3	4	5
20. Without realizing, I produce the English word faster when speaking Spanish	1	2	3	4	5
21. There are situations in which I always switch between languages	1	2	3	4	5
22. There are topics in which I always switch between languages	1	2	3	4	5

More Items on Next Page

	Never	Rarely	Sometimes	Most of the Times	Always
23. When I speak with family members at home, I use more than one language	1	2	3	4	5
24. When I speak with colleagues at school, I use more than one language	1	2	3	4	5
25. When I speak with friends during leisure time, I use more than one language.	1	2	3	4	5

Appendix B

Summary of Exploratory Factor Analysis Results for Patterns of Language Behavior Measure Using Maximum Likelihood Estimation and Oblimin (Direct Quartimin) Rotation (N = 120)

	Item Loadings		
Item	Low Language Control	High Language Control	h^2
How often do you switch languages between sentences when speaking at home?	**.883**	-.222	.668
I do not realize when I switch languages during conversation	**.681**	.003	.465
I do not realize when I mix languages during conversation	**.671**	.01	.456
When I speak with family members at home, I use more than one language	**.669**	-.145	.389
There are situations in which I always switch between languages	**.612**	.156	.477
How often do you mix words of different languages when speaking at home?	**.605**	.132	.449
There are topics in which I always switch between languages	**.518**	.234	.423
How often do you switch languages between sentences when speaking in places other than home, school, and work?	**.511**	.066	.294
It is difficult to control the language switches in a conversation	**.468**	.095	.265
Produce Dominant Faster when speaking NonDominant	**.455**	-.092	.181
Forget NonDominant Language	**.38**	.007	.147
How often do you mix words of different languages when speaking at school?	-.036	**.809**	.631

Item	Low Language Control	High Language Control	h^2
How often do you switch languages between sentences when speaking at school?	.127	**.544**	.369
How often do you mix words of different languages when speaking at work?	.235	**.536**	.445
When I speak with colleagues at school, I use more than one language	-.165	**.526**	.233
How often do you speak two or more languages in the same environment?	.029	**.493**	.255
How often do you mix words of different languages when speaking in places other than home, school, or work?	.299	**.468**	.423
Produce NonDominant Faster when Speaking Dominant	-.033	**.398**	.149
How often do you switch languages between sentences when speaking at work?	.225	**.344**	.232
Forget Dominant Language	-.018	**.337**	.109
Forget Dominant, Produce in NonDominant	.159	**.327**	.175
Forget NonDominant, Produce in Dominant	.283	.210	.173
When I speak with friends during leisure time, I use more than one language	.244	.197	.138
Speak only one language in one environment	-.203	-.131	.08
Eigenvalue	5.947	1.678	
% of vairance	24.779	6.992	

Note: Items in italics are reverse-coded items. Factor loadings over .32 appear in bold.

Vita

Christian Ruiz-Ortiz is a Ph.D. student in the Bilingualism, Language, and Cognition program at the University of Texas in El Paso, where he also received both his Bachelor of Science in Psychology in 2015 and Master of Arts in Experimental Psychology in 2023. As an undergraduate student, he developed a profound interest in cognitive psychology, pushing him to pursue an undergraduate research assistant position in the Cognition and Aging Laboratory under the supervision of Dr. Ashley S. Bangert, which later became his graduate supervisor when he started the doctoral program in the Fall of 2018. Before his graduate training, he received vast teaching experience across different academic institutions throughout his hometown in El Paso, Texas, teaching courses such as psychology, statistics, computer literacy, communication, and writing, where he discovered his passion for education. As a graduate student, he was drawn to the intricacies of language and cognition and began focusing on exploring the consequences of bilingualism on executive functions.

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